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An Economic Analysis of Generation IV Small Modular Reactors

J. S. Stewart, A. D. Lamont, G. S. Rothwell, C. F. Smith, E. Greenspan, N. Brown, A. Barak

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Jeffrey S. Stewart, Lawrence Livermore National Laboratory
Alan D. Lamont, Lawrence Livermore National Laboratory
Geoffrey S. Rothwell, Stanford University
Craig F. Smith, Lawrence Livermore National Laboratory

Collaborators
Ehud Greenspan, U.C. Berkeley
Neil Brown, Lawrence Livermore National Laboratory
Ami Barak, U.C. Berkeley

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ABSTRACT

This report examines some conditions necessary for Generation IV Small Modular Reactors (SMRs) to be competitive in the world energy market. The key areas that make nuclear reactors an attractive choice for investors are reviewed, and a cost model based on the ideal conditions is developed. Recommendations are then made based on the output of the cost model and on conditions and tactics that have proven successful in other industries.

The Encapsulated Nuclear Heat Source (ENHS), a specific SMR design concept, is used to develop the cost model and complete the analysis because information about the ENHS design is readily available from the University of California at Berkeley Nuclear Engineering Department. However, the cost model can be used to analyze any of the current SMR designs being considered.

On the basis of our analysis, we determined that the nuclear power industry can benefit from and SMRs can become competitive in the world energy market if a combination of standardization and simplification of orders, configuration, and production are implemented. This would require wholesale changes in the way SMRs are produced, manufactured and regulated, but nothing that other industries have not implemented and proven successful.

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1.0 Introduction

The objective of this study is to determine if Generation IV Small Modular Reactors (SMRs) can be competitive in the world energy market, in particular with Combined-Cycle Gas Turbines. In our initial review, we completed the following tasks:

- Developed a cost model for the economic evaluation of an SMR that identifies cost reduction areas.
- Evaluated the cost of electricity from a small reactor as a function of (1) where it is located and (2) the number of units installed over time.
- Identified improvements in the design or configuration that might lead to a reduction in the cost of electricity or other advantages.
- Identified key areas of uncertainty (i.e., fuel enrichment costs, regulatory constraints) in which further study has the potential to demonstrate that SMRs can be economically competitive.

We used an LLNL cost model to analyze a specific SMR, the Encapsulated Nuclear Heat Source (ENHS), and determined the cost of generating electricity with the ENHS and how these costs can be reduced. (Table 1 provides a summary of the ENHS and eight other SMR designs and concepts that can also be analyzed using this model.)

Finally, we explored numerous ways of reducing the cost of SMRs. The airplane manufacturing industry provided the best example for SMRs to follow because of the similarities in size, cost, and complexity between airplanes and SMRs. We specifically looked at the design, manufacture, and distribution of airplanes and concluded that SMRs can be competitive with CCGTs in most regions of the world, if the target cost-objectives are met through mass production.

Table 1: Summary of small modular reactor designs and concepts (Magwood 2001, 29)

	CAREM*	ENHS	IRIS-50*	KLT-40*	MRX*	MSBWR*	RS-MHR*	TPS*	4S*
Designer	CNEA	UCB	W	OKBM	JAERI	GE/ PURDUE U.	GA	GA	CRIEPI
Type	Integral PWR	LMR	Integral PWR	PWR	Integral PWR	BWR	HTGR	PWR	LMR
Rating	25 MWe	50 MWe	50 MWe	35 MWe	30 MWe	50 MWe	10 MWe	16.4 MWe	50 MWe
Fuel type	UO_2 pins	U–Zr metal	UO_2 pins	U-Al alloy	UO_2 pins	UO_2 pins	UO_2 particles	U–ZrH pins	U–Zr metal
Fuel enrichment	3.40%	13%	4.95%	—	4.30%	5%	19.90%	19.90%	± 15%
Refueling frequency (% replaced)	~1 yr (50%)	15 yr (100%)	5–9 yr	2–3 yr (100%)	~4 yr (50%)	10 yr	6–8 yr	1.5 yr (50%)	10 yr (100%)

* CAREM (Argentina), IRIS-50 (International Reactor Innovative and Secure), KLT-40 (Russia), MRX (Japan), MSBWR (Modular Simplified Boiling Water Reactor), RS-MHR (Remote-site modular helium reactor), TPS (TRIGA Power System), and 4S (Japan).

2.0 COMPETITIVE ELECTRICITY MARKETS

Although electricity can be generated in many ways, this study compares the cost of generating electricity with an SMR to that generated with a Combined-Cycle Gas Turbine (CCGT). According to the Energy Information Administration (EIA), natural gas is expected to be the fastest growing component of world energy consumption. Gas use is projected to almost double from 84 trillion cubic feet in 1999 to 162 trillion cubic feet in 2020. With an average annual growth rate of 3.2%, the share of natural gas in total primary energy consumption is projected to grow from 23% to 28% with the largest growth in gas use expected in Central and South America and in developing Asia. The developing countries as a whole are expected to add a larger increment to gas use by the year 2020 than industrialized countries. Among the industrialized countries, the largest increases are expected for North America (mostly the United States) and Western Europe (DOE EIA 2001, Oil Markets).

Although the cost of generating electricity with a CCGT varies from region to region, we assume that the capital costs of CCGTs are the same throughout the world, given the world market for CCGT equipment. We assume that the overnight construction cost of a CCGT is \$500/kW, based on a rough average of EIA estimates (Table 2). With a real discount rate of 10% and a construction time of two years, interest during construction is approximately \$50/kW. With a 20-year capital recovery period, the capital recovery factor is

$$\left[0.10\cdot(1.10)^{20}\right]/\left[(1.10)^{20}-1\right]=11.75\% \ .$$

TABLE 2: Cost and performance characteristics for fossil-fueled generating technologies—three cases* (DOE EIA 2001, Performance Characteristics)

	Overnight cost including contingencies in 2000	Overnight cost including contingencies and learning effects *			Heat rate in 2000	Heat rate		
	Reference	Reference case	High fossil case	Low fossil case 2	Reference	Reference case	High fossil case	Low fossil case 2
	1999\$/kW	1999\$/kW	1999\$/kW	1999\$/kW	Btu/kWh	Btu/kWh	Btu/kWh	Btu/kWh
Conventional Combined Cycle	445				7687			
2005		440	440	440		7343	7343	7343
2010		434	434	434		7000	7000	7000
2015		429	429	429		7000	7000	7000
2020		423	423	423		7000	7000	7000
Advanced Combined Cycle	576				6927			
2005		551	548	576		6639	6193	6985
2010		499	494	576		6350	5534	6985
2015		478	474	576		6350	4874	6985
2020		466	458	576		6350	4874	6985

* Source: AEO2001 National Energy Modeling System runs: AEO2001.D101600A, HFOSS01.D101800B, LFOSS01.D101700A.

The annual capital cost is \$65/kW or \$65,000/MW. If the CCGT is dispatched two-thirds of the time (i.e., 5800 hours per year), the capital cost per MWh is approximately \$11.

The cost of natural gas varies from region to region and from period to period. In the Latin America and Caribbean region, the price ranges from \$20/MBtu in Barbados to less than \$1/MBtu in Venezuela. Further, the heat rate for CCGTs varies under different assumptions concerning the number of CCGTs built and advances in the technology. Assuming a heat rate of 7000 Btu/kWh, the average total cost of generating electricity varies as a function of the price of natural gas (Table 3). In most regions, electricity generated with CCGTs is more than \$30/MWh.

If new nuclear power technologies can generate electricity at less than \$30/MWh, they will be able to compete on an economic basis with natural gas in most regions of the world. If the average cost were greater than \$30/MWh, a more detailed analysis would have to be conducted to determine if there were other factors that make nuclear power attractive.

TABLE 3: Cost of electricity generation with natural gas (\$US/MWh) (DOE EIA 2001, Cost of Elect. Gen.)

Region	Country	1994	1995	1996	1997	1998	1999
EEU	Czech	35.20	38.78	39.95	37.85	39.19	36.19
EEU	Hungary	25.92	26.51	26.93	33.07	33.03	34.71
EEU	Slovakia	31.05	33.52	32.95	33.66	33.00	30.18
LAM	Barbados	NA	NA	NA	NA	153.12	153.12
LAM	Bolivia	NA	NA	NA	NA	21.73	21.17
LAM	Chile	NA	NA	NA	NA	22.67	NA
LAM	Colombia	NA	NA	NA	NA	33.91	NA
LAM	Mexico	25.06	21.87	26.75	28.52	25.36	26.58
LAM	Trinidad	NA	NA	NA	NA	18.14	18.13
LAM	Venezuela	NA	NA	NA	11.66	12.87	14.91
NAM	United States	26.24	24.55	29.05	30.32	27.63	29.01
PAO	Japan	36.70	38.78	40.23	48.34	NA	NA
PAS	Taiwan	58.31	56.87	52.28	56.02	49.61	46.57
WEU	Austria	38.22	NA	NA	NA	NA	NA
WEU	Belgium	29.65	30.35	32.52	34.37	NA	NA
WEU	Finland	29.96	36.74	37.23	33.63	32.15	30.02
WEU	Germany	36.75	41.80	41.45	38.89	NA	NA
WEU	Ireland	29.45	31.99	30.83	29.56	29.29	28.59
WEU	Italy	31.87	33.97	NA	NA	NA	NA
WEU	Netherlands	31.18	36.44	35.20	33.81	32.49	NA
WEU	Spain	36.40	40.46	41.96	36.00	33.63	32.15
WEU	Turkey	36.42	39.59	41.04	44.22	40.23	38.91
WEU	United Kingdom	31.96	31.80	31.09	32.73	33.28	31.36

3.0 The Economics of Small Modular Reactors

In the following sections we develop a cost model for an SMR based on the characteristics of a specific SMR, the Encapsulated Nuclear Heat Source (ENHS), which illustrates some of the cost elements used in our cost model. We then develop a base case and sensitivity analysis, and compare those results with a cost analysis on SMRs published by the U.S. Department of Energy (DOE).

3.1. Encapsulated Nuclear Heat Source

The ENHS is a concept being developed under the Nuclear Energy Research Initiative program by a consortium led by the University of California at Berkeley. (Selected design parameters are given in Table 4.) It is a liquid-metal-cooled reactor (LMR) that can use either lead (Pb) or a lead-bismuth (Pb–Bi) alloy as the reactor coolant. As opposed to the traditional liquid-metal coolant, sodium (Na), lead-based coolants are chemically inert with air and water, have higher boiling temperatures, and have better heat transfer characteristics for natural circulation.

The ENHS has a core life of 15 years and uses natural circulation to cool the reactor core and produce steam to drive its turbine. It relies on autonomous control, that is after the reactor is brought to full power, variation in power output follows the electricity generating needs automatically (load-following) by using temperature feedback from the varying steam pressure and feed-water flow (Figures 1 and 2).

TABLE 4: Selected design parameters of representative ENHS modules for 125 MWt (Greenspan, Saphier, et all. 2001, v)

Design parameter	ENHS1	ENHS2
Primary Pb coolant circulation	100% natural	With lift-pump
Average linear heat rate (W/cm)	60	60
Average discharge BU* (MWd/tHM)	52,000	52,000
Core life* (effective full power years)	20	20
BU reactivity swing	<1$	<1$
Maximum excess reactivity	<1$	<1$
Core height (m)	1.25	1.50
Core diameter (m)	1.98	1.87
Fuel rod diameter (cm)	1.0	1.0
Clad thickness (cm)	0.1	0.1
Lattice (hexagonal) pitch (cm)	1.45	1.50
Overall module height (m)	19.6	10.1
Outer module diameter (m)	3.24	3.35
Number of rectangular channels in IHX	135	245
Inner dimensions of channel (cm × cm)	40 × 2.5	50 × 1.0
IHX channel length (m)	13	6
Weight of fueled module for shipment (ton)	360	300
Coolant core inlet/outlet temperature (°C)	400/564	400/543
Primary-to-secondary mean ΔT (°C)	49.1	47.3
Number of steam generators per ENHS	8	8
Steam generator module diameter (m)	1.0	1.0
Active length of SG tubes (m)	7.5	7.5

*Limited by radiation damage to clad @ $4 \times 10^{23}\ n/cm^2$ >0.1 MeV.

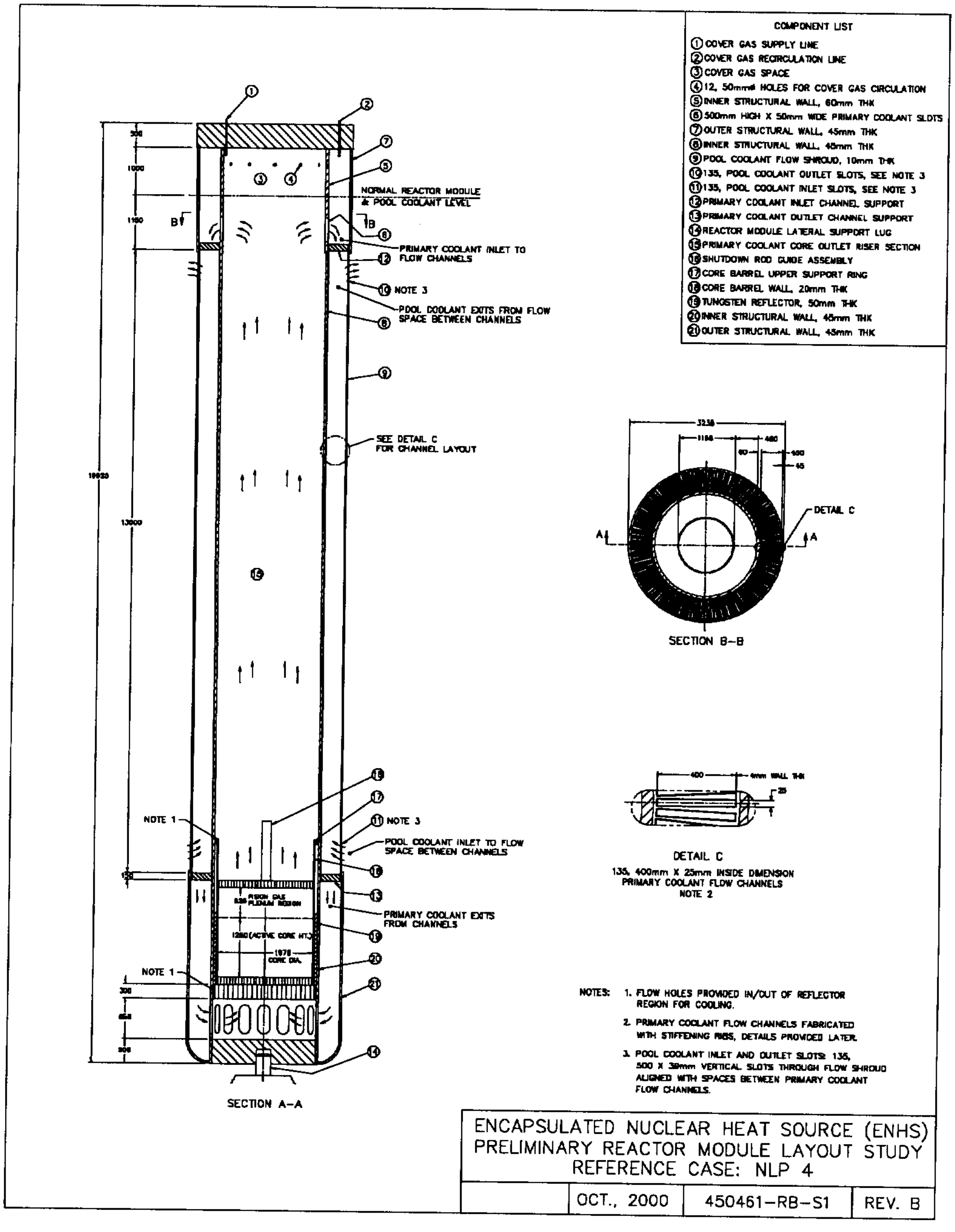

Figure 1: Design of the ENHS (Greenspan, Saphier, et all. 2001, vi)

Cost elements included for typical generating unit

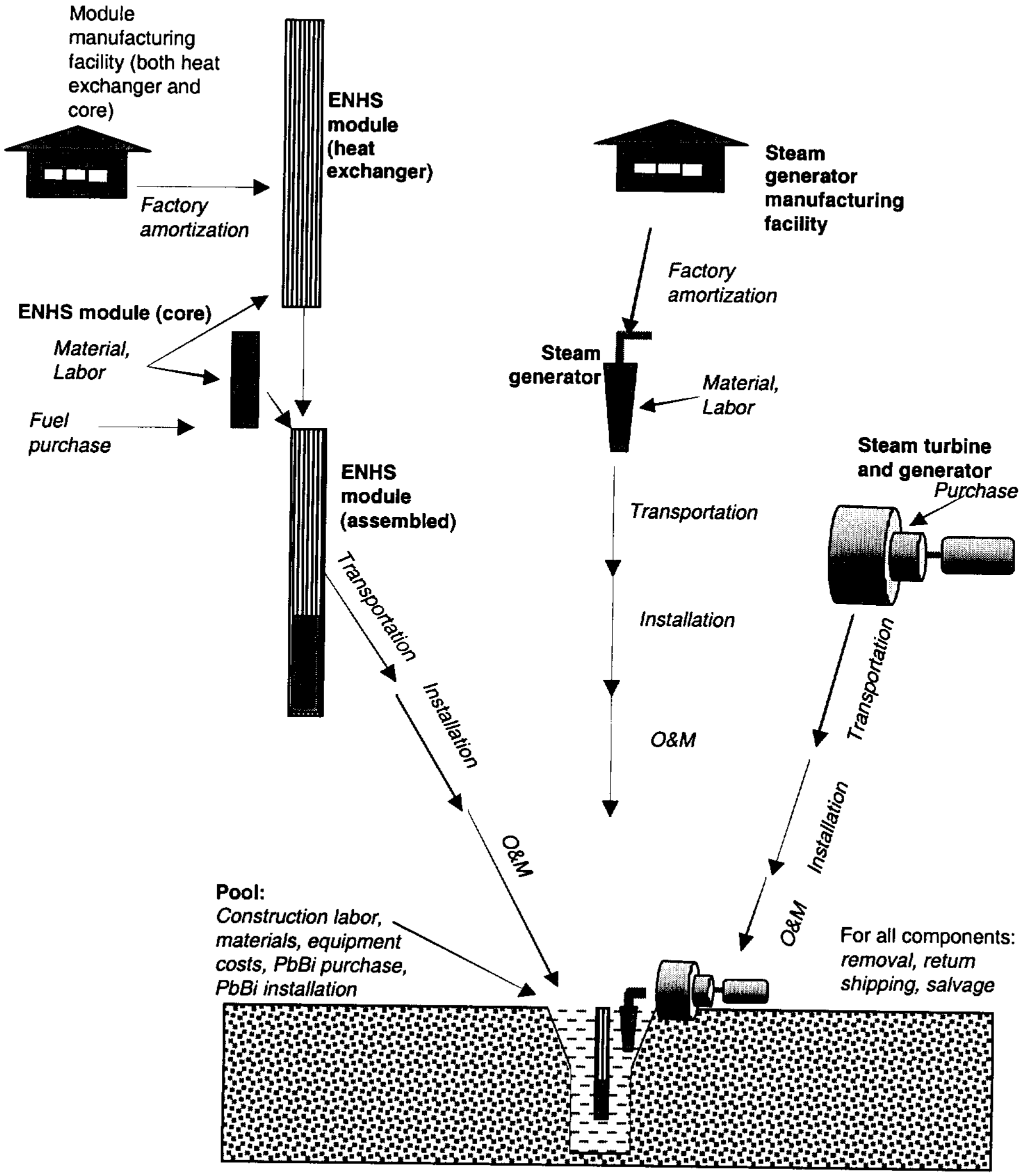

Figure 2: The cost elements of a typical generating unit

The ENHS design encapsulates the reactor core inside its own vessel, with no external piping connections. The core is located in a central vertical cylinder inside the vessel. The annular region, between the central cylinder and the outer wall of the reactor module, is constructed as a counterflow heat exchanger. The ENHS module is inserted into a large pool of secondary molten metal. Heat generated in the core is carried upward by the primary molten-metal coolant to the top of the vertical cylinder where openings connect to the primary side of the annular heat exchanger region. The primary coolant flows downward and back through another set of openings under the reactor core. The molten metal in the pool enters the secondary side of the annular heat exchanger through openings in the reactor vessel at the bottom, and exits through another set of openings at the top. In this manner, the heat generated in the core is passively transferred to the secondary pool, through the counterflow heat exchanger in the reactor vessel, without using any piping connections.

The steam generators, which are separate modules, are also inserted into the secondary pool, adjacent to the reactor vessel module. The molten metal in the pool enters the poolside of the steam generator, through openings near the top of the steam generator, and exits near the bottom of the steam generator after transferring heat to the water in the steam generator. Water also circulates through the steam generator using natural circulation—no pumps are used in this reactor system. The ENHS concept can automatically load-follow over a wide power range.

3.1.1. Fuel Characteristics

The ENHS fuel is a metallic alloy of uranium and zirconium (U–Zr) or uranium, plutonium, and zirconium (U–Pu–Zr), and it is stable under irradiation. The fuel is contained in cylindrical fuel pins with a large fission gas plenum above to accommodate high burnup of the fuel and the resulting expansion from gaseous fission products. The reactor can operate at full power for 15 years using either U–Pu–Zr metallic fuel having about 11% plutonium, or U–Zr metallic fuel using uranium enriched to 13% U^{235}. The core consists of fuel rods without channels. The central location is reserved for a large safety element, which can assure complete reactor shutdown. The core is surrounded by six segment-reflectors made of tungsten.

Fuel is the most expensive component of the ENHS, as it must be mined, processed and enriched before use, and then disposed of or reprocessed after use. The cost of enriching the fuel increases exponentially with higher enrichment, yet it is anticipated that the cost can be reduced given a large demand for enrichment.

3.1.2. Safety Aspects

The ENHS concept is inherently safe; it is characterized by a large thermal inertia due to the large inventory of primary and secondary liquid-metal coolant. In all accident sequences, heat is transferred by conduction and natural convection to the vessel boundary while the fuel and cladding temperatures remain significantly below safety limits.

3.1.3. Diversion Resistance

The ENHS can operate at full power for 15 years. It is manufactured and fueled in the factory, and then shipped to the site as a sealed unit with solidified Pb (or Pb–Bi) filling the vessel to the upper level of the fuel rods. At the end of its life, the ENHS module must be removed from the reactor pool and stored on site until the decay heat drops to a level that allows the coolant to solidify—approximately 6 months. The module, with the solidified coolant, then serves as a shipping cask. Its compact, sealed design, combined with refueling every 15–20 years, provides high proliferation resistance.

3.1.4. Transportation and Installation

To increase the potential market for SMRs, early consideration must be given to transportation and installation issues. If the goal is to increase the number of potential sites, then it is necessary to build modules that can be transported by ship, barge, and rail. Each mode of transportation has constraints on dimension and weight, which are not likely to change in the next 20–30 years, so we assume future standards are likely to be similar to current ones.

The ENHS module is shipped to the site as a sealed unit with no mechanical connections between the reactor module and the secondary system. It is as easy to install and replace as a battery. After installation, hot coolant is pumped into the vessel to melt the solid lower part, a process that takes a few days to complete. At the end of its life, the module with the solidified coolant is returned in a shipping-over pack that is provided to shield it and enhance cooling.

3.1.5. Potential Sites

Siting requirements can be established by the manufacturers and regulators during the original design. To meet the goal of basic and stable design (see section 4.0), enough sites must be pre-identified to ensure that the fixed plant design has enough potential market share to be competitive. Seismic and other natural phenomena must be accounted for in the initial design. Once the physical site requirements are determined, a Geographic Information System can be used to screen for potential sites: data sets containing seismic and geological information, current grid locations, current and future grid capacities, transportation, and demographic data. This information provides the manufacturers, investors, and utilities with advanced siting data that usually requires a number of years to complete for each potential site. Prescreening sites will reduce the time required for siting individual plants.

3.1.6. Operation and Maintenance

The ENHS is inexpensive to operate and maintain because 1) it has a simple design and few parts, which require fewer people to operate and maintain, 2) it requires infrequent module replacement and short-term fuel storage on site (six months every fifteen years), which reduces personnel requirements, and 3) it has inherent security features, which allow plants to rely more heavily on local government security instead of employing large in-house security staffs. Reduced on-site staff can also be realized through service agreements with contractors, which would eliminate on-site support staff and allow utilities with common designs to rely on outside expertise.

3.1.7. Replacement/Dismantlement

SMRs are designed for modules to be replaced easily with minimal disruption to service. The ENHS design anticipates several days for actual replacement of an old module with a new one. The old module must then cool at the site for six months, before it can be shipped back to the factory for reuse or dismantlement.

3.1.8. Capacity Factors

SMRs can expect to have higher capacity factors than Light Water Reactors (Appendix 1). This study uses 90% for a base case assumption although higher capacity factors may actually be realized.

3.1.9. Overall Assessment

The ENHS concept offers a safer system than current reactors that is characterized by low waste, high proliferation resistance, high uranium utilization, and simplicity of operation. If the concept can meet its design goals, it would revolutionize the way SMRs are built, regulated, and even financed.

3.2. Economic Evaluation of an SMR

3.2.1. Description of System Configuration and Life Cycle

To compute the cost of electricity for a single generating unit, we estimate the cost based on a revenue requirements analysis. In such an analysis, we compute the annual income required for the entire generating unit to earn a given rate of return, and then divide the required revenue by the annual energy output to find the required price of energy from a single unit.

To determine the total annual cost of the generating unit, we divide the system into components, such as the ENHS and the steam generators, and develop a cost estimate for each by computing the costs involved in building, installing, operating, and removing each component. The sum of the annual cost of each component is the total annual cost of the generating unit.

3.2.2. Generating Unit Configuration

A single unit consists of one steam turbine/generator unit driven by one or more ENHS modules. The ENHS modules and the associated steam generators are contained within a single pool of molten Pb–Bi. (Figure 2 provides the schematic layout of a single generating unit.)

For convenience in this analysis, the ENHS module is divided into (1) the core and (2) the heat exchanger. These parts are built separately and then joined; even though they will probably be built in the same facility, we estimate the costs separately. The amortization of the facility cost is estimated and applied only to the heat exchanger cost.

3.2.3. System Life Cycle Description

Components will either be purchased or built in central facilities and transported to the site for installation and operation. Initially, a full complement of components will be delivered and installed at the site, however, the components have different lifetimes. The pool is estimated to be on the order of 60 years, and the other components are significantly shorter-lived, requiring a series of component replacements during the life of the pool. As each component is replaced, it is returned to its factory for refurbishment, salvage, or disposal.

Unlike a conventional reactor, it is expected that the process of replacing components will have only a small effect on the unit's availability. The replacement of some components, such as steam generators, may not require shut down of the unit at all; replacement of other components, even an ENHS, may shut down a unit for only a few days.

3.2.4. Life Cycle Cost Analysis of Each Component

Because it is not practical to specify the life of a generating unit as a whole, we have computed the electricity cost by calculating the annual cost of each component and taking the sum of the components to determine the annual cost of the generating unit as a whole. We then divide that amount by the anticipated electrical energy generation to compute a cost-per-unit energy.

Some of the components of the system are standard and are available from existing suppliers of production facilities, so it is assumed that these components will be purchased. They include the fabricated, enriched fuel and the steam turbine (including all the appurtenant equipment such as the condenser, re-heaters, feed-water system, and controls). It is also assumed that a facility will be built to fabricate the nonstandard components, including the module (both the core and the heat exchanger) and the steam generators. The cost of the components includes the amortization of the fabrication facility.

The cost analysis includes the entire life cycle of the facility and its components from initial fabrication (or purchase) through salvage. Thus, for every component (e.g., steam generator), we estimated a series of cost items (Table 5) and determined the time at which they are incurred (first year of the component's life, ongoing, or last year of the component's life). The cost of each item was then converted to an annual cost over the life of the component. We used an 8% discount rate for the base case.

Table 5: Items included in life cycle cost analysis

Cost item	Approach to cost estimation
Initial acquisition cost:	
Purchased components:	
Purchase of components	Estimated the cost of actual materials based on historic prices.
Fabricated components:	
Capital cost of fabrication facility amortized over the total number of components	Estimated a cost and a useful life for the fabrication facilities. This cost was then amortized over the life of the facilities, and the resultant annual cost was distributed over the estimated number of units per year.
Cost of materials for fabrication	Computed based on the total mass of material (e.g., stainless steel, concrete).
Cost of labor for fabrication or construction	Estimated the time in terms of factory labor time (man-hours) required for each operation.
Transportation to/from site:	Considered both land and sea transportation, and estimated costs per kilometer for each component. A representative assumption was made for the land and sea distances. The cost of return transportation was assumed to be the same as the cost of transportation to the site.
Installation at site:	Estimated on-site labor time, which includes construction equipment for excavating the pool and for installing the components. It is assumed that the construction equipment is also used for the initial installation.
Operation and maintenance over lifetime:	Estimated annual labor time and costs of consumables.
Removal at the end of lifetime:	Estimated on-site labor time.
Salvage/disposal:	The salvage value may be positive or negative (a positive value indicates that useable material was extracted from the used component, such as the stainless steel from steam generators; a negative value indicates that some additional cost was incurred, for example for disposal).

3.2.4.1. Uranium Fuel Costs

We assumed nuclear fuel would be purchased, and because fuel for this reactor has a relatively high enrichment (12.5%), we made a separate estimate to determine its cost per kilogram:

- The cost of the feed and separative work units (SWUs) used to reach the required level of enrichment, using equations for an ideal enrichment cascade (Villani 1979).
- The conversion cost of U_3O_8.
- The cost of fuel fabrication.

For the base case, we assumed the cost of the U_3O_8 to be $13.5/lb or $30/kg (rounding off), which corresponds to projections made by the U.S. Department of Energy's (DOE) Energy Information Administration (EIA) for the years 2010–2015. We determined the enrichment cost by the cost of SWUs. The EIA reports that current prices are near $85/SWU and are expected to remain at that level for the foreseeable future, so we have used $85/SWU for the base case (http://www.eia.doe.gov/).

3.2.4.2. Fabrication Facility Capital Cost

We also considered changes in the production rate and what effect that has on the results. As the production capacity of the fabrication facilities is increased, the capital cost of the fabrication facilities increases, although not linearly. We used a scaling formula in our calculations to project the increased capital cost of the facilities as a function of the increased production capacity, where the base cost of the facility and a base production rate are specified. Then, the cost of a facility having a different production rate was scaled from the base facility. The following equation was used (Humphreys and Wellman 1987)

$$CapitalCost(Rp) = \left(\frac{Rp}{Rp\_base}\right)^k \cdot CapCost\_base,$$

where

Rp = the production rate of the new facility,
Rp_base = the capacity of the base facility,
$CapCost\_base$ = the capital cost of the base facility,
k = a scaling exponent (generally ≤ 1.0).

In this case, as in most, we estimated that economies of scale would lower unit costs as the production rate increased. This was a result of a combination of improved efficiencies in labor, capital use, and overhead.

3.2.4.3. Interest During Construction and Testing

To evaluate the full costs of constructing a unit, we took into account the interest during construction, which depends on the actual pattern of payments during construction. In this case, the fuel is a very large fraction of the total cost, so a precise calculation depends on exactly when the fuel is purchased. The error is small for short construction periods—amounting to a few percent of the total cost—but for construction lasting five years or more, the timing of the fuel purchase has a significant impact on the cost estimate.

In a precise calculation of the interest during construction, the sum of the over-interest payments would be taken for each year during construction, but that would make the years-of-construction a variable and result in a cumbersome calculation. Instead, we use an approximation that assumes the total overnight cost is paid out uniformly during the construction period. The interest on the first year's payment is computed and we assume that the average payment is about half that amount. The average interest is then multiplied by the number of construction years. The following equation is used

$$Interest\ \ During\ \ Construction = N \cdot \frac{\left(\frac{TotCost}{N}\right) \cdot (1+\text{int})^{N-1} - \frac{TotCost}{N}}{2},$$

where

N = number of years of construction,
$TotCost$ = total overnight cost of the unit,
int = interest rate.

(Note that in this calculation, it is assumed that payments are made at the year-end.)

This equation is quite accurate for short construction times, but at eight years, the estimated interest during construction is about 15% too high, and for construction times greater than eight years, the error grows rapidly. This study did not look at the effects of higher interest rates during the construction phase.

We also took into account that the unit does not generate commercial power during the testing period, even though construction is complete and all funds are paid. Because of this, interest costs accumulate until the unit begins commercial production. This was calculated as the interest charge on the full overnight cost of the unit, plus the interest during construction.

3.3. Base Case and Sensitivity Analysis

We analyzed a base case and a series of variations, where the assumptions in the base case were set to values that were believed to be achievable based on the ENHS design. Appendix 2 lists the input parameter values for the base case and provides a description of each one, Table 6 lists the values used for the alternative cases, and Appendix 3 provides a detailed breakdown of the costs for all of the cases.

Table 6: Values of variables used for cases analyzed

Case variation	Description
Base	Values as noted
Site Labor 2×	Site labor cost is doubled
Factory Labor 2×	Factory labor cost is doubled
High SWU Price	SWU price is set to $100/SWU
High U_3O_8 Price	U_3O_8 price is set to $50/kg
High Interest Rate	Interest rate is set to 10%
Lower Capacity Factor	Capacity factor is set to 80%
Longer Construction Period	Construction period is set to eight years, plus six months for testing

Figure 3 illustrates the breakdown of the annualized costs by cost category (e.g., labor and materials) for the base case and Figure 4 illustrates a similar breakdown by the components of the generating unit (e.g., turbines and steam generators). The values in Figure 4 reflect all of the costs associated with each component over its lifetime including purchase, shipment, installation, operation, and removal. Table 7 summarizes capital and annual costs and the resulting cost of electricity for each of the cases analyzed.

In the base case, the overall cost of electricity was estimated at 2.96 ¢/kWh (i.e., $29.60/MWh, or slightly less than electricity from a CCGT). Figure 3 shows that the cost of nuclear fuel is the largest single cost component for the unit, so cases that vary the costs of enrichment and U_3O_8 increase the cost of electricity by up to 10%. Increasing the construction time, the most expensive case, increases the cost by approximately 21%.

The costs of site labor and factory labor have been roughly estimated in this analysis. Our results show that factory labor has relatively little impact on the overall cost, since it accounts for a small fraction of the total cost; however, site labor has a significant effect, since it accounts for nearly 30% of the total annual cost. Doubling the site labor costs increases the total cost by approximately 20%.

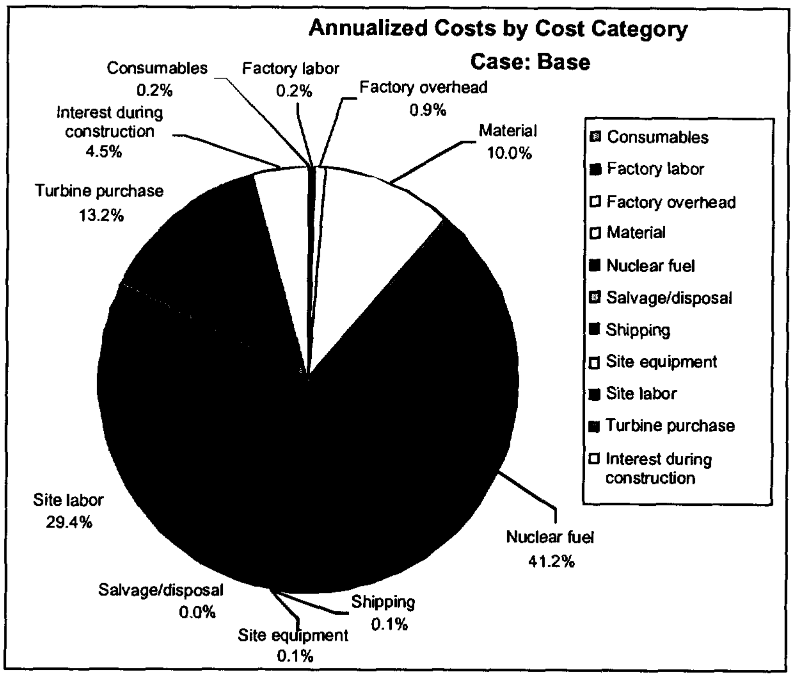

Figure 3: Breakdown of annualized costs by cost category for base case

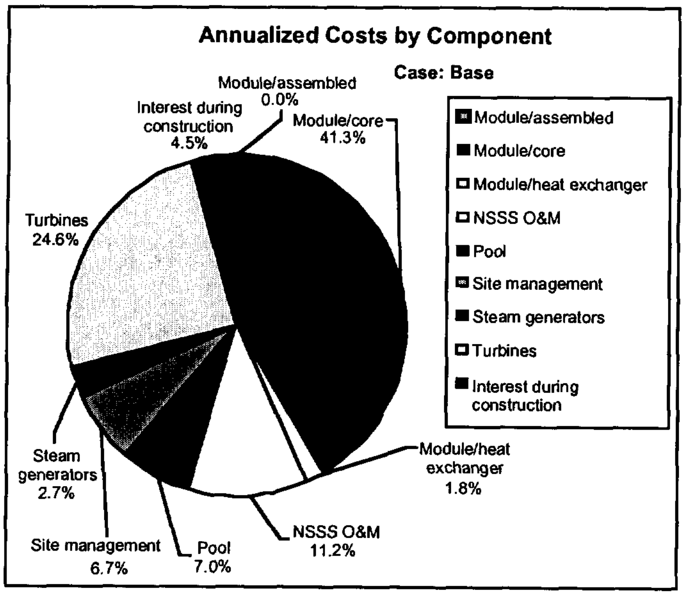

Figure 4: Breakdown of annualized costs by generating unit component

TABLE 7: Summary of the capital costs and cost of electricity for cases analyzed

	Base	Site labor 2×	Factory labor 2×	High SWU price	High U_3O_8 price	High interest rate	Lower capacity factor	Longer construction period
Unit capital cost ($/kWe)								
Unit capital cost (w/o) fuel	913	925	920	923	931	957	913	1,523
Unit capital cost for fuel	1087	1087	1087	1207	1302	1087	1087	1087
Total unit capital cost	**2000**	**2012**	**2007**	**2130**	**2233**	**2044**	**2000**	**2610**
Annual costs ($M/yr)								
Annualized capital cost w/o fuel*	3.96	4.01	3.99	4.00	4.03	5.00	3.96	6.42
Annualized fuel cost	5.54	5.54	5.54	6.15	6.63	6.39	5.54	5.54
Total annualized capital cost	**9.50**	**9.54**	**9.53**	**10.15**	**10.66**	**11.39**	**9.50**	**11.96**
O&M costs	**2.19**	**4.35**	**2.19**	**2.19**	**2.19**	**2.19**	**2.19**	**2.19**
Busbar costs (¢/kWh)								
Capital	1.00	1.02	1.01	1.01	1.02	1.27	1.13	1.63
O&M	0.56	1.10	0.56	0.56	0.56	0.56	0.63	0.56
Fuel	1.40	1.40	1.40	1.56	1.68	1.62	1.58	1.40
Total	**2.96**	**3.52**	**2.97**	**3.13**	**3.26**	**3.45**	**3.34**	**3.59**

* Includes the end-of-life costs (e.g., removal and dismantlement) for components.

3.4. Comparison of Cost Results to Other Studies

We compared the results in our study to those from the DOE Office of Nuclear Energy, Science and Technology's *Report to Congress on Small Modular Nuclear Reactors* (2001) (Tables 8 and 9) and found that (1) the capital costs in their study range from 2.9 to 7.2¢/kWh compared with a base case cost of 1¢/kWh in our study, (2) operation and maintenance costs range from 1.5 to 2.4¢/kWh compared with our cost of 0.56¢/kWh, and (3) fuel costs estimated from 1 to 1.1¢/kWh compared with our estimate of 1.4¢/kWh (this could be due to our assumption that a fuel fabrication plant will be constructed).

Table 8: Cost information for a generic 50 MWe SMR, (year 2000 dollars)*

Item	Minimum	Maximum
Unit capital cost ($/kWe)	$1950	$5067
Levelized period (years)	20	20
Levelized capital cost (M$/year)	$10.9	$28.3
O&M cost (M$/year)	$5.5	$9.4
Fuel costs (M$/year)	$3.7	$4.2

* These cost estimates are for an "*n*th-of-a-kind" plant.

Table 9: Estimated 50 MWe SMR busbar cost (¢/kWh, year 2000 dollars)

	Minimum	Maximum
Capital	2.9	7.2
O&M	1.5	2.4
Fuel	1	1.1
Total	**5.4**	**10.7**

The cost for the SMR we reviewed is considerably less expensive than the estimates in the *Report to Congress on Small Modular Nuclear Reactors*. The reason for the difference is difficult to determine without more information on the assumptions used in that report.

4.0 Reducing Costs of SMRs

This section compares the manufacture and operation of SMRs with that of airplanes, to suggest methods for reducing the cost of generating electricity from these nuclear power plants.

4.1. Opportunities to Reduce Costs of Manufacture and Design

Manufacture and design has significantly changed during the last several decades due to the increased power of computers and better software packages. For example, computer aided design (CAD) programs have allowed many companies to move away from labor and capital-intensive design, engineering, and test manufacturing. In particular, Boeing Corporation (2001, 777 Facts) has benefited by using this technique and by implementing major changes in the following areas to reduce costs:

- Reducing the number of prototypes to zero, thus making the first plane a commercially ready unit.
- Reducing customer options.
- Offering only one engine choice on the newest Boeing 777.

4.1.2. Design and Manufacturing Cost Reductions Achieved in the Boeing 777

In the late 1980s, Boeing set out to design a new 100% digital airplane, the 777, which has more than three million parts. The complexity and cost of developing such an airplane was evident in the number of companies willing to take that risk; McDonnell Douglas and Lockheed dropped out of the market and left Boeing as the only large commercial aircraft manufacturer in the United States.

Since the 1980s, Boeing has gambled several times with new business approaches to reduce costs. The approach that is relevant to the nuclear power industry is Boeing's Tailored Business Streams (TBS) model (Boeing 2001, DCAC/MRM Overview). This model is similar to the way the automobile industry has done business for decades—limiting customer choice in order to streamline design and production of parts—but is rare among manufacturers of complex and expensive items such as large airplanes.

Boeing first invested in streamlining its aircraft order, configuration, and production computer systems. The new system, called Define and Control Airplane Configuration/Manufacturing Resource Management (DCAC/MRM), replaced 450 computer and software programs that were used to make previous models with four commercial, off-the-shelf applications. DCAC/MRM allows better and faster communication between work teams and is so successful that Boeing is proposing it to some of its suppliers (Boeing 2001, DCAC/MRM Overview).

The TBS model also streamlines Boeing's design and manufacture of aircraft by limiting customer choice, reusing parts, limiting the design of new parts, and thereby limiting the approval process required by the Federal Aviation Administration (FAA). To do so, Boeing gathered customer input during the design stage of the new aircraft. This was crucial because, unlike earlier models, Boeing would limit its offerings so that custom designs would occur on a limited basis. The FAA requires approval of all new designs and changes, so Boeing's previous practice of designing parts and manufacturing plans for each individual plane, and then giving customers the option to change configurations, engines, and other component parts, resulted in production-line disruptions during the FAA approval process.

Boeing's TBS approach divides the business into three "streams" to arrive at simpler, reusable, more cost-effective processes and solutions:

- TBS 1—parts and processes that go into every plant. Called basic and stable because they do not require new design, customer decisions, or planning for each new customer introduction.
- TBS 2—parts and processes that are reusable. Includes options that are common to planes and options that have been approved and are available for a customer to order. Design is available for reuse and is known to be compatible with other option combinations.
- TBS 3—parts and processes that are unique, custom designed, or need special tooling, and whose designs are not meant to be reused. Requires additional flow-time compared to a similar TBS 2 part.

Figure 5 illustrates the old system of responding to customer orders compared with the new system, the goal of which is to reduce parts entering the TBS 3 stream. Examples of Boeing's prior business stream and the new TBS goal are illustrated in Figures 6 and 7.

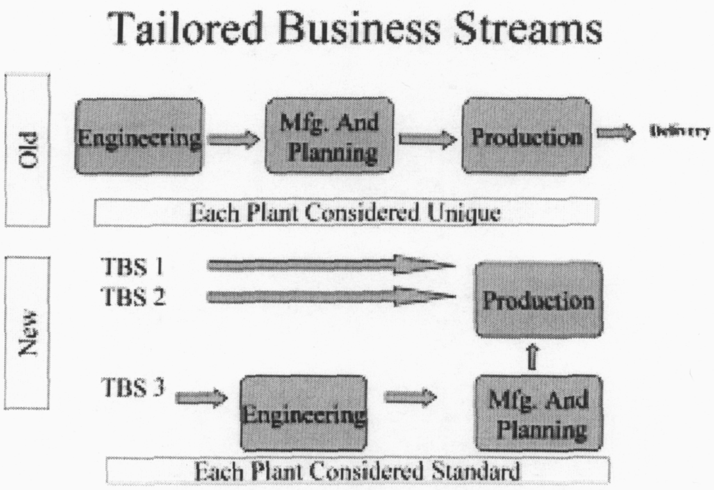

Figure 5: Illustration of the old and new TBS models

Boeing is moving toward low-cost, agile manufacturing capability as opposed to risky multibillion-dollar aircraft designs (Proctor 1999). Stating that one of the goals is to have a Boeing production line resemble a Toyota factory, Boeing has claimed the following successes:

- Streamlined aircraft order, configuration, and production systems.
- Reduced the average assembly workflow at Boeing's Auburn plant from 27.5 to 8 days.
- Reduced average revisions per order from 17 to 0.
- Doubled the annual inventory "turn rate" to 9.
- Reduced the unit cost to 80% of their 1992 level.
- Reduced 30 software computer systems to 1 at the Auburn site.
- Reported less overtime.
- Reorganized aircraft design and production engineering into a platform-based structure with an expected savings of 15%.

As a result of implementing TBS, Boeing also claims its sales staff can now configure a customer's order on the spot with a laptop computer, rather than sifting through stacks of documents.

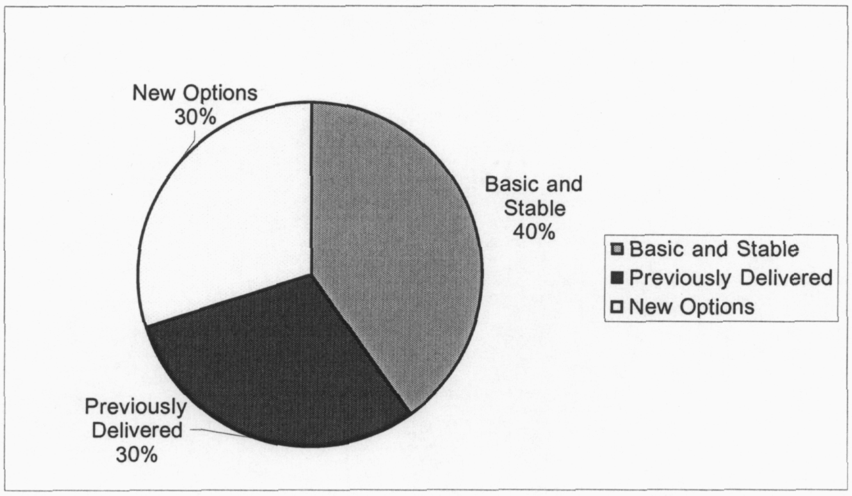

Figure 6: Illustrative example of Boeing's business stream under previous management policies

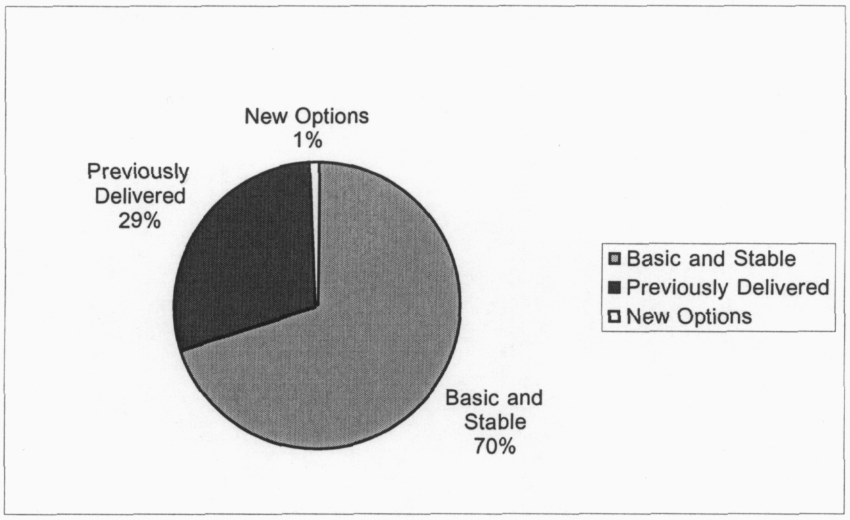

Figure 7: Illustrative example of Boeing's business stream under new management policies

Another cost-saving measure that Boeing recently implemented was an exclusive engine supplier arrangement with General Electric (GE) (Business Week 1999). Previously, Pratt and Whitney and Rolls Royce each had 35% of the engine market for Boeing 777s with GE receiving the remaining 30%. Prior to this exclusive arrangement, GE had invested over $2 billion into developing its powerful GE90 engine that was made exclusively for Boeing's 777 model. After GE won the bid—a contract that was the first of its kind—GE estimated sales of up to $15 billion, which allowed it to recoup its investment.

This exclusive contract and its implicit maintenance rights not only benefited GE, but promised to reduce costs to Boeing by simplifying its assembly process and maintenance costs. The cost savings could then be passed on to customers as a trade-off for choice, which is crucial to Boeing's success if it is to compete with Airbus, a competitor that continues to offer engine options to customers.

Even though the arrangement appears to be beneficial to Boeing, it is considered risky. Boeing is gambling that its customers are willing to give up selecting engines—an arrangement airlines have grown accustomed to—for a savings in overall costs. Boeing now must make the price attractive enough to the airlines so they are not swayed toward Airbus (Business Week 1999).

Applied to this study, these business practices (i.e., standardizing, streamlining, and simplifying orders, configuration, and production) can benefit the nuclear power industry as they have the automobile and aircraft industries.

4.1.3. Design and Construction Cost Reduction with SMRs

Standardization of design has proven to lower costs of manufactured goods as evident throughout most sections of the economy. To move from custom power plants to standard design requires meeting with utilities in advance to ensure that the design meets the needs of enough utilities to obtain a profitable market share. The inherent advantages of factory fabrication have also been recognized in many industries and are already being considered for modules in many Generation IV reactors (Magwood 2001).

Standardization also allows for faster production, in part because design shops do not have to be reconfigured and workers do not have to be retrained for each model. Suppliers can reduce costs by standardizing components, and those savings can be filtered throughout the industry. The design and manufacturing learning curve (DOC 1988), a recognized feature of manufacturing and assembly facilities, can be achieved in the nuclear power industry giving it similar advantages that competing electric generation plants share.

In a review of nuclear power plants with more than one reactor of the same design, we observed that sites with multiple units had similar historic capacity factors. This does not indicate whether a plant will perform well or poorly, but rather it shows that similar designs have similar reliabilities. When we looked at the entire population of plants, the variability was high, indicating that many designs give greater variability in capacity factors. This suggests that if good designs were replicated, then the industry's performance would become consistently reliable. Appendix 1 gives a more detailed explanation.

Another change to previous nuclear reactor designs is the idea of a sole supplier contract. By reducing the number of potential suppliers, suppliers can be asked to offer better terms and to guarantee performance. Sole-supplier contracts for turbines and steam generators fit in this category. Offering one manufacturer greater volume makes it easier for that supplier to improve and guarantee the reliability of their components.

As discussed previously, one such arrangement exists between Boeing and GE for airline engines. GE provides maintenance of its engines at a fixed cost as part of its right to be the sole supplier of engines for Boeing's line of 777s. This gives GE incentive to look for ways of improving engine design and reliability. Repair-prone engines erode the profit margins of manufacturers and customers; improved engine reliability helps the manufacturer and relieves airlines of unexpected maintenance expenses.

Standardizing the processes of designing, engineering, manufacturing, and installing can greatly reduce the lead-time needed to build a nuclear power plant. According to the DOE (DOC 1988, 28-30), the average time spent designing and licensing a nuclear power plant in the United States in 1987 was 14 years (Figure 8) compared to a lead time of 84 months, or 7 years, for a typical coal-fired power plant. The additional seven years to begin operating a nuclear power plant make it difficult to compete with coal, and especially oil- and gas-fired plants that take only 5 years to build. A 14-year time span also makes it very difficult for investors who must try to predict the energy market 14 years out from their initial investment date.

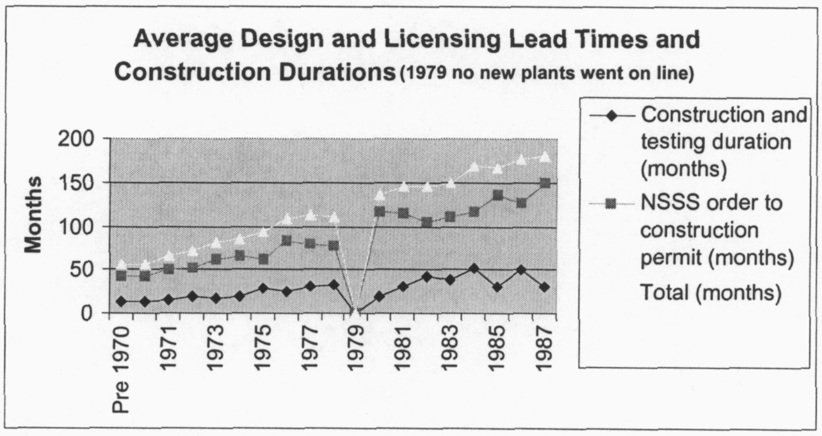

Figure 8: Lead times for design, licensing, and construction (DOC 1988, 28)

The DOE developed cost estimates for standardizing an 1100-MWe nuclear power plant and gave an 11% cost reduction for second and subsequent Large Scale Prototype Breeder (LSPB) designs. This is used to estimate the *n*th-of-a-kind (NOAK) cost.

The DOE and United Engineers also developed a reference capital investment cost for an 1100-MWe nuclear power plant to be opened in 2000. The plant's cost estimate reflected improved construction experience, proposed construction practice improvements, and nuclear regulatory and licensing reforms. Table 10 compares these potential industry improvements to the median current experience.

Table 10: Cost reductions due to plant standardization

	United Engineer's median experience	Reference plants EEDB-9
Lead time	12	8
Man-hour/kWe	26	14
Indirect cost	No change	Decrease

A reduction in indirect costs for the EEDB-9 plants was the result of standardizing the plants and decreasing the engineering required for regulatory mandated back-fitting. The estimated savings from these reforms was approximately 50%, reducing indirect costs from $7.9 to $4 billion (DOC 1988, 30).

We propose going even further by implementing changes that would make an SMR's lead time, standardization, and licensing resemble those for coal-, oil- and gas-fired power plants.

4.2. Reduction of Licensing and Construction Times

Figure 8 illustrates the length of time required to build a new nuclear power plant in the United States through 1987, but does not include testing of the plant. The Vogtle Electric Generating plants Units 1 and 2 required 50 months of testing after construction was completed, with 30 months dedicated to the first unit and 20 to the second (Georgia Power 1990). Testing schedules alone are longer than the full construction times required for oil-, gas-, and coal-fired plants. A 30-month testing schedule in our cost model increases the cost of the plant by approximately $15 million or roughly 15% of the plant's total cost, however, SMRs can be successfully constructed, tested, and put on the grid in less than four years prior to more stringent regulations and site requirements (Magwood 2001, 8). A licensing approach similar to the model developed by the FAA and aircraft industry can benefit the nuclear power industry.

4.2.1. Licensing Aircraft at the Federal Aviation Administration

In the aircraft industry, the FAA requires every new design of a plane—not the plane itself—to receive a Type Certification (TC) before it can fly commercially in the United States. A TC, as defined by the FAA in rule §21.41, includes the type design, the operation limitations, the type certificate data sheet, the applicable regulations, and any other conditions or limitations prescribed by the Administrator (DOT 2000). The FAA has procedures (detailed in Figure 9) to approve the design and manufacture of major components, for engineering compliance, and for the manufacturer's flight test results. Part of the TC process also requires FAA approval of the facility that will manufacture the plane. This takes several days for an established company such as Boeing, but longer for a new company or facility. After approving designs and production facilities, the FAA grants an Experimental Airworthiness Certificate, and more than 2000 test flight hours must be logged before a TC is granted and commercial production can begin.

According to Ed Kupcis (2001), Boeing's Chief Engineer for Certification, the average time for an established company to move from concept to production of a large transport plane is five years, during which time the FAA and company designers are actively engaged.

Each new plane must receive an Airworthiness Certificate from the FAA, but after reaching an agreeement with the FAA more than 40 years ago, Boeing is now authorized to approve subsequent planes (Kupcis 2001). This agreement allows Boeing to appoint Designated Engineering Representatives (DERs) and Designated Manufacturing Inspection Representatives (DMIRs) from its own staff to monitor and review engineering and manufacturing quality and compliance with FAA rules. DERs spend 10–20% and DMIRs spend 100% of their time ensuring that Boeing is complying with rules and meeting FAA-approved engineering and manufacturing specifications and guidelines. Flight tests for second through *n*th production are usually completed in one to three flights before DMIRs issue Airworthiness Certificates.

Kupcis (2001) maintains that this arrangement of self-certification works well. There are enough built-in incentives (lives, capital investment, negative publicity, and market share) to ensure Boeing's strict compliance and it enables them to produce up to twenty-eight 737s a month (almost one per day) and 500 to 600 planes a year. If the FAA required the same certification for each plane as it did for the first, it would take years for Boeing to test each plane.

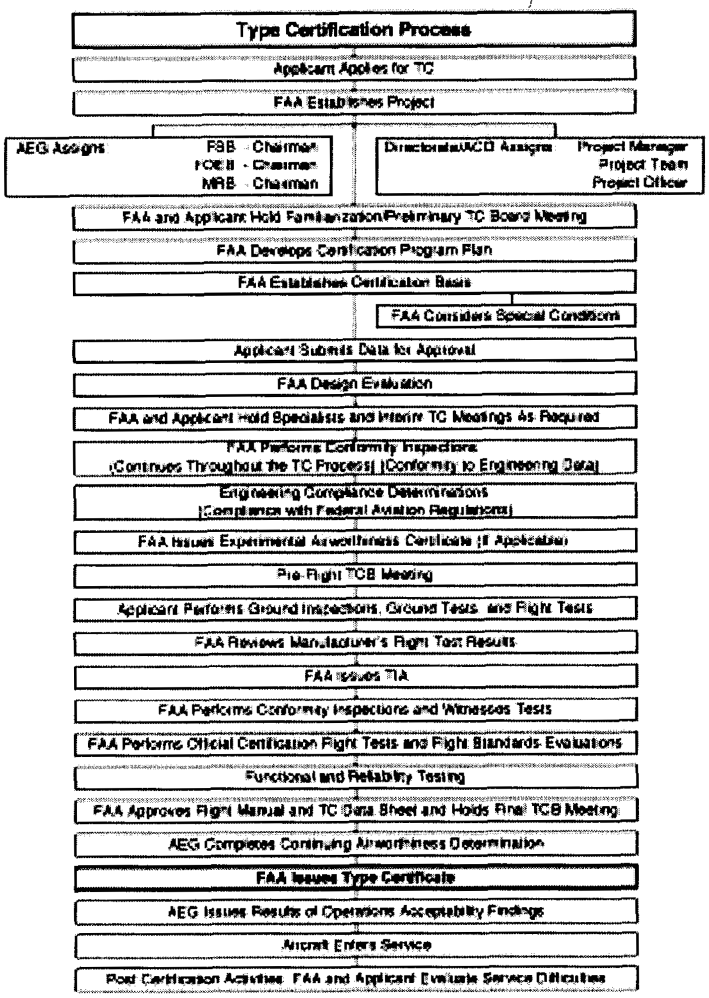

Figure 9: FAA approval of aircraft (DOT 2000)

The major airline manufacturers are also working with the FAA and Europe's Joint Aviation Authority (JAA) to streamline the licensing process between Europe and the United States (Kupcis 2001). Currently, each authority accepts test results from the other but when one agency has requirements that its counterpart does not, the manufacturer is required to meet those additional standards. The goal of the manufacturers is to have identical standards for both agencies.

The standardization of nuclear power plants would allow for a design and approval process similar to the one followed by Boeing and the FAA. The first design and model would go through several years of testing and certification, but subsequent plants would not, as long as the design and parts did not change. Using this model, it is feasible to certify a Generation IV plant for operation after approximately six months of on-site testing and licensing.

4.2.2. CERTIFICATION REQUIREMENTS FOR SMRS

The Nuclear Regulatory Commission (NRC) focuses on three areas of nuclear power plant safety (Magwood 2001, 34):

- Reactor safety
- Radiation safety for workers and the public
- Security and protection of the plant against sabotage or other security threats.

SMR design improvements have resulted in not only simpler designs and shorter licensing and testing cycles, but have also included inherent safety and safety systems that operate passively, as opposed to systems that solely rely on actively engineered safety systems. The following excerpt from the *Report to Congress on Small Modular Nuclear Reactors* (Magwood 2001, 34-35) summarizes how the SMR designs fit within these safety concerns:

> *Initiating Events*—Most SMR designs and concepts are simpler than existing light-water reactor (LWR) designs. This reduces the number of systems required to provide and support the heat transport and electrical generation of the plant. In addition, inherent safety features reduce the number and complexity of accident mitigation systems. The resulting reduction in mechanical components and associated control systems greatly reduces the potential for equipment failure that leads to plant shutdowns, large changes in the plant's power output, or accidents.
>
> *Mitigating Systems*—SMR designs typically take a different approach to mitigating accidents by using the design to reduce the potential for an accident occurring and to reduce the severity if one does occur. For example, a negative temperature coefficient is maintained for the reactor core, and passive and inherent safety systems are used to remove the human error element that can potentially affect proper plant response to accident conditions.
>
> *Barrier Integrity*—Some SMR designs rely on the integrity of the fuel to retain fission products under all postulated conditions, instead of relying on a pressure-retaining containment building to contain any fission products released as the result of a reactor accident. This makes verification of fuel integrity extremely important because, unlike a containment building that can be periodically leak-rate tested, verification of fuel integrity after the initial fabrication is difficult. However, if fuel performance can be guaranteed, the SMR can be much simpler and easier to maintain through the elimination of a conventional containment building.
>
> *Emergency Preparedness*—An SMR will still have comprehensive emergency plans to respond to a possible accident. However, the extent of the emergency plan will be based on the worst-case, source-term for radioactive release estimated by the accident analysis. It is possible that evacuation of the public beyond the site boundaries will not be necessary because of the estimated small-source term.
>
> - Occupational Radiation Safety and Public Radiation Safety: These regulations will not change.
> - Physical Protection: Nuclear Plants are required to guard vital plant equipment. There will be fewer attractive materials easily accessible with most SMR designs.

4.3. APPROACHES FOR FINANCING SMRS

To increase customer base, businesses and financial institutions have created numerous ways to ease the financing of products. One way is through leasing. The following example illustrates the positive effect that leasing had on the airline industry and was chosen because of the similarities in cost between airplanes and SMRs.

In the airline industry, leasing companies have led to an increase in airplane sales. Inexpensive leases, as opposed to purchasing an entire fleet of aircraft, allow existing airlines to easily expand and new passenger and freight companies to enter the market with less capital. This is evident in the many new low-fare and regional carriers that have sprung up in the last decade, such as Southwest Airlines.

Three of the companies involved in the airplane or airplane-parts leasing business are General Electric Capital Aviation Services (GECAS), debis AirFinance (a division of DaimlerChrysler Group), and Curtis Power Company (CPC). (The latter is a recently formed joint venture between GECAS and General Electric Engine Services.) The following summaries illustrate the successes these leasing companies have had:

- GECAS's portfolio consists of more than 1100 planes and 170 customers in 60 countries, making it one of the largest companies in the airline leasing business. Its leasing terms range from 3 to 12 years (<http://www.gecas.com/>). In July 2000, GECAS announced it would purchase up to 149 Boeing jetliners to add to its existing fleet (GECAS 2000, Commits to Boeing). The first 74 orders are valued at $5.5 billion. The largest and most expensive planes in the fleet include the Airbus 320 and Boeing 747, 757, 767, and 777. These planes range in price from $72 to $231.5 million (Boeing 2001, Airplane Prices).
- GECAS also announced in 2000 that Canadian-based WestJet Airlines agreed to lease up to 70 new Boeing 737-600/700 series aircraft (GECAS 2000, WestJet to Order). Leasing terms were not released but an estimated price range (based on a $2.8–3.8 billion retail value) is $250–400 million per year, assuming interest is between 8% and 10%. With the ability to lease planes and engines and purchase engine maintenance agreements, airline companies reduce their risk of incurring unexpected expenses and extra staffing.
- Started in 1995, debis AirFinance is a mid-size airline leasing company. In 1997, it purchased its first new Boeing airplanes and a year later new Airbus airplanes. By the end of 2000, debis AirFinance had reported a fleet of 220 aircraft. The company assets exceeded $4.5 billion with a five-year accumulated profit of $150 million, and had a pre-tax return on equity at 24.1% in 2000 (debis AirFinance 2002). Leasing terms require 2–10 year commitments with insurance for plane losses payable to debis AirFinance and all operating expenses covered by the lessee (<http://www.debisairfinance.com/>).
- Curtis Power Company's (CPC) president, Harry Hubschman, stated that the company "was formed in response to customer demand for easier financing..." for one of the most expensive parts of an airplane, the engines (GECAS 1999, Invests in CPC). CPC offers leases and maintenance for engines, the advantage of which includes the flexibility to quickly and inexpensively expand and contract. For the cost of one plane (up to $230 million), an airline can lease more than 10 planes. Less capital requirements to start or increase the size of an airline reduce the risk to investors.

A nuclear-power-plant leasing company can follow an approach similar to that used by airline leasing companies; however, leasing an SMR has some obvious differences from leasing a plane. First is the inherent mobility of an airplane—a plane can be returned in a matter of hours or days whereas an SMR requires months. Second, some components and infrastructure are not easily transferable to a new utility, and third, a new utility needs some lead-time to prepare a site for a new SMR. Given these differences, a deposit equivalent to two years payment is assumed sufficient to cover the expense of an order cancellation or default. Four of the cases tested with this report's cost model (Appendix 3, Table A3) are illustrated below in a leasing scenario.

Tables 11 and 12 consider four leasing scenarios at 8% and 10% interest. The four cases selected show the largest cost impediments to deploying an SMR.

TABLE 11: Leasing scenario for each option at 8% interest

	Base case	High SWU enrichment ($100/SWU)	High U_3O_8 price ($50/kg)	Longer construction period
Plant cost ($)	100,071,069	106,554,742	111,683,127	100,023,046
Interest rate (%)	0.08	0.08	0.08	0.08
Capacity factor (%)	0.90	0.90	0.90	0.90
Lease term (years)	30.00	30.00	30.00	30.00
Deposit ($)	(17,778,112)	(18,929,968)	(19,841,051)	(17,769,581)
Monthly cost ($)	(740,755)	(788,749)	(826,710)	(740,399)
Cost of electricity ($/MWh)	(22.86)	(24.34)	(25.52)	(22.85)

TABLE 12: Leasing scenario for each option at 10% interest

	Base case	High SWU enrichment ($100/SWU)	High U_3O_8 price ($50/kg)	Longer construction period
Plant cost ($)	100,071,069	106,554,742	111,683,127	100,023,046
Interest rate (%)	0.10	0.10	0.10	0.10
Capacity factor (%)	0.90	0.90	0.90	0.90
Lease term (years)	30.00	30.00	30.00	30.00
Deposit ($)	(21,230,928)	(22,606,494)	(23,694,524)	(21,220,739)
Monthly cost ($)	(884,622)	(941,937)	(987,272)	(884,197)
Cost of electricity ($/MWh)	(27.30)	(29.07)	(30.47)	(27.29)

An SMR owner can reduce the traditional operational and maintenance staff by leasing some of the maintenance services. Maintenance contracts for major components, such as turbines and steam generators, can be entered into with manufacturers as part of the leasing agreement. Maintenance can be done more efficiently by those contracted to repair potentially hundreds to thousands of these identical parts and will free the utility from maintaining a staff for routine procedures.

The success of this type of arrangement is contingent on a market for used nuclear power reactors and components. Given the success of leasing arrangements for both airlines and manufacturers, it would appear that further study with private industry is warranted.

5.0 CONCLUSIONS AND FURTHER RESEARCH

In this report, we demonstrated that SMRs can be competitive by adapting successful business practices from other industries. As Figure 3 illustrates, the high cost of nuclear fuel and site labor significantly affect the cost for SMRs. It is also apparent that standardization is important for the success of SMRs as it lowers the cost of factory labor and overhead.

Of the scenarios examined, the length of construction time is the most significant factor to increase cost, which makes it difficult for SMRs to compete with other sources. Lengthening the construction time from three to eight years for initial order to full power increases the overall cost by 21%. An overhauled regulatory environment is crucial in reducing the construction time cost in the base case. The current regulatory system adds cost to nuclear reactors that coal and natural gas do not have, and that extra burden, in addition to any unforeseen delays, makes nuclear power a higher-risk investment than those fuel sources. If the regulatory environment can guarantee shorter and more predictable schedules, investors will find nuclear power more attractive. This is an important area for further research.

The final significant finding is the potential for leasing. The development of semi-transportable SMRs makes it possible to offer leasing arrangements similar to those in the aircraft manufacturing industry. The much lower capital requirement makes it easier for a region to purchase SMRs, and while financing could be offered to the other types of energy plants, it is evident from the aircraft industry that doing so would increase the market for energy generation and thus the demand for SMRs. Further research involving the financial community could lead to financial breakthroughs, particularly for SMRs.

APPENDIX 1: LISTING OF AVERAGE LOAD FACTORS FOR NUCLEAR REACTORS WORLDWIDE

The average load factors for nuclear reactors worldwide were examined with a one way analysis of variance implemented with the Stata statistical software package. The conclusions are:

1. The Bartlett test of equality of variances is accepted, with *P*-value 0.263. That is, the probability is 0.263 under the hypothesis of equal variances that the sample variances will be as spread out as those in the dataset. (These are the sample variances for those sites with two or more units.) A *P*-value under 0.05 is considered significant (suggesting inequality of variances). We feel comfortable with the assertion that the unit-to-unit variability in capacity is about the same for each site.
2. The common variance is estimated to be 21.1. By taking the square root, we estimate the common within site (i.e., unit-to-unit) standard deviation to be 4.6.
3. The *F*-test for equality of mean capacities is significant at a level less than 0.0005. In other words, it is implausible that the various sites all have the same mean capacity. In particular, it is clear that the Browns Ferry site has significantly lower mean capacity than many of the other sites. (The two sites with zero capacities were not used in the analysis.)

Table A1: Average load factors for reactors worldwide

Average load factors 1992–1999					
Name	**Country**	**Lifetime**	**Name**	**Country**	**Lifetime**
Atucha	Austria	68.4	Hamaoka 1	Japan	58.6
Embalse	Austria	80.6	Hamaoka 2	Japan	72.9
Doel 1	Belgium	83.7	Hamaoka 3	Japan	80.3
Doel 2	Belgium	78.6	Hamaoka 4	Japan	81.7
Doel 3	Belgium	85.3	Ikata 1	Japan	76.7
Doel 4	Belgium	79.3	Ikata 2	Japan	82
Tihange 1	Belgium	80	Ikata 3	Japan	75
Tihange 2	Belgium	84.5	K-Kariwa 1	Japan	79.1
Tihange 3	Belgium	86.9	K-Kariwa 2	Japan	83.3
Angra 1	Brazil	28.1	K-Kariwa 3	Japan	83.2
Kozloduy 1	Bulgaria	60.4	K-Kariwa 4	Japan	79.5
Kozloduy 2	Bulgaria	64.6	K-Kariwa 5	Japan	82.3
Kozloduy 3	Bulgaria	65.2	K-Kariwa 6	Japan	79.4
Kozloduy 4	Bulgaria	67.3	K-Kariwa 7	Japan	77.7
Kozloduy 5	Bulgaria	27.4	Mihama 1	Japan	45.4
Kozloduy 6	Bulgaria	44.4	Mihama 2	Japan	56.9
Bruce 1	Canada	59.9	Mihama 3	Japan	71.3
Bruce 3	Canada	67.5	Ohi 1	Japan	57.7
Bruce 4	Canada	63.6	Ohi 2	Japan	66.3
Bruce 5	Canada	80.2	Ohi 3	Japan	84.9
Bruce 6	Canada	78.3	Ohi 4	Japan	78.7

Average load factors 1992–1999					
Name	**Country**	**Lifetime**	**Name**	**Country**	**Lifetime**
Bruce 7	Canada	80.4	Onagawa 1	Japan	75.7
Bruce 8	Canada	78.3	Onagawa 2	Japan	76.2
Gentilly 2	Canada	74	Sendai 1	Japan	78.8
Pickering 1	Canada	59.7	Sendai 2	Japan	81.1
Pickering 2	Canada	57.2	Shika 1	Japan	78.3
Pickering 3	Canada	65.4	Shimane 1	Japan	72.6
Pickering 4	Canada	62.9	Shimane 2	Japan	82
Pickering 5	Canada	74.4	Takahama 1	Japan	61.2
Pickering 6	Canada	80.3	Takahama 2	Japan	61.7
Pickering 7	Canada	82.3	Takahama 3	Japan	81.6
Pickering 8	Canada	77.3	Takahama 4	Japan	81.7
Pt Lepreau	Canada	83.4	Tokai 2	Japan	73.8
Beznau 1	Switzerland	79.9	Tomari 1	Japan	81.3
Beznau 2	Switzerland	86.6	Tomari 2	Japan	80.5
Goesgen	Switzerland	86.1	Tsuruga 1	Japan	67.1
Liebstadt	Switzerland	83.5	Tsuruga 2	Japan	79.4
Muehlenberg	Switzerland	81.5	Ignalina	Lithuania	50.1
Dukovany 1	Czech Republic	79.6	Ignalina	Lithuania	55.1
Dukovany 2	Czech Republic	79.4	Laguna Verde 1	Mexico	68.1
Dukovany 3	Czech Republic	78.6	Laguna Verde 2	Mexico	75
Dukovany 4	Czech Republic	80.5	Borssele	Netherlands	79.8
Biblis A	Germany	65.9	Cernavoda 1	Romania	82.4
Biblis B	Germany	65.1	Barsebaeck 1	Sweden	74.9
Brokdorf	Germany	83.9	Barsebaeck 2	Sweden	76
Brunsbuttel	Germany	51.8	Forsmark 1	Sweden	79.1
Emsland	Germany	92.3	Forsmark 2	Sweden	78.9
Grafenrheinfeld	Germany	84.3	Forsmark 3	Sweden	82.5
Grohnde	Germany	89.7	Oskarshamn 1	Sweden	59.5
Gundremmingen B	Germany	78.1	Oskarshamn 2	Sweden	74.4
Gundremmingen C	Germany	77.2	Oskarshamn 3	Sweden	81.6
Isar 1	Germany	71.9	Ringhals 1	Sweden	63
Isar 2	Germany	84.7	Ringhals 2	Sweden	63
Kruemmel	Germany	72.9	Ringhals 3	Sweden	66.7
Mulheim Karlich	Germany	7.4	Ringhals 4	Sweden	72.7
Neckar 1	Germany	77.8	Koeberg 1	South Africa	61.9
Neckar 2	Germany	91.1	Koeberg 2	South Africa	63
Obrigheim	Germany	77.7	Kori 1	South Korea	68.1
Philippsburg 1	Germany	72.1	Kori 2	South Korea	82.2
Philippsburg 2	Germany	87.7	Kori 3	South Korea	79.1
Unterweser	Germany	79.4	Kori 4	South Korea	82.1
Almaraz 1	Spain	75	Ulchin 1	South Korea	80
Almaraz 2	Spain	82.9	Ulchin 2	South Korea	82.8
Asco 1	Spain	78.9	Ulchin 3	South Korea	72.3
Asco 2	Spain	85.1	Wolsong 1	South Korea	83.4
Cofrentes	Spain	85	Wolsong 2	South Korea	80.4

Average load factors 1992–1999					
Name	**Country**	**Lifetime**	**Name**	**Country**	**Lifetime**
Garona	Spain	71.6	Wolsong 3	South Korea	88.1
Trillo 1	Spain	81.4	Yonggwang 1	South Korea	80.4
Vandellos 2	Spain	81.9	Yonggwang 2	South Korea	75.9
Zorita	Spain	61.7	Yonggwang 3	South Korea	79.9
Belleville 1	France	66.3	Yonggwang 4	South Korea	85
Belleville 2	France	64.6	Bohunice 1	Slovakia	69.7
Blayais 1	France	71.6	Bohunice 2	Slovakia	72.4
Blayais 2	France	74.4	Bohunice 3	Slovakia	75.9
Blayais 3	France	76	Bohunice 4	Slovakia	77.4
Blayais 4	France	74.1	Krsko	Slovenia	73.5
Bugey 2	France	61.9	Chinshan 1	Taiwan	72.3
Bugey 3	France	62.4	Chinshan 2	Taiwan	73.6
Bugey 4	France	62.2	Kuosheng 1	Taiwan	71.3
Bugey 5	France	65.7	Kuosheng 2	Taiwan	74
Cattenom 1	France	62.2	Maanshan 1	Taiwan	69.1
Cattenom 2	France	68.3	Maanshan 2	Taiwan	74.6
Cattenom 3	France	72.7	Arkansas 1	United States	65.4
Cattenom 4	France	72.6	Arkansas 2	United States	68.8
Chinon B1	France	71.8	Arnold	United States	63.6
Chinon B2	France	72.1	Beaver Valley 1	United States	56.9
Chinon B3	France	71.7	Beaver Valley 2	United States	71.7
Chinon B4	France	74.3	Braidwood 1	United States	69.8
Cruas 1	France	67.6	Braidwood 2	United States	77.8
Cruas 2	France	69.8	Browns Ferry 1	United States	23.5
Cruas 3	France	70.5	Browns Ferry 2	United States	49.6
Cruas 4	France	70.9	Browns Ferry 3	United States	35.5
Dampierre 1	France	67.8	Brunswick 1	United States	56.6
Dampierre 2	France	65.5	Brunswick 2	United States	54.4
Dampierre 3	France	69.1	Byron 1	United States	71.6
Dampierre 4	France	69.5	Byron 2	United States	76.3
Fessenheim 1	France	67.5	Callaway 1	United States	83.6
Fessenheim 2	France	67.5	Calvert Cliffs 1	United States	67.4
Flamanville 1	France	64.1	Calvert Cliffs 2	United States	70.8
Flamanville 2	France	66.1	Catawba 1	United States	72.9
Golfech 1	France	71.3	Catawba 2	United States	74.4
Golfech 2	France	65.2	Clinton	United States	50.4
Gravelines B1	France	66.1	Comanche Peak 1	United States	78.2
Gravelines B2	France	71.2	Comanche Peak 2	United States	77.4
Gravelines B3	France	72.8	Cook 1	United States	61.2
Gravelines B4	France	72.6	Cook 2	United States	56
Gravelines C5	France	71.7	Cooper	United States	61.4
Gravelines C6	France	73.4	Crystal River 3	United States	0
Nogent 1	France	63.6	Davis Besse 1	United States	60.1
Paluel 1	France	70.6	Diablo Canyon 1	United States	78.7
Paluel 3	France	68.9	Diablo Canyon 2	United States	80.3

Average load factors 1992–1999					
Name	**Country**	**Lifetime**	**Name**	**Country**	**Lifetime**
Paluel 4	France	68.9	Dresden 2	United States	58.4
Penly 1	France	70.6	Dresden 3	United States	55.5
Penly 2	France	73.6	Farley 1	United States	75.7
Phenix	France	40.1	Farley 2	United States	82
St Alban 1	France	61.4	Fermi 2	United States	51.3
St Alban 2	France	59.3	Fitzpatrick	United States	61.8
St Laurent B1	France	60.9	Fort Calhoun 1	United States	96.9
St Laurent B2	France	65.1	Ginna	United States	73.2
Tricastin 1	France	69.4	Grand Gulf	United States	72.8
Tricastin 2	France	71.3	Hatch 1	United States	0
Tricastin 3	France	75.7	Hatch 2	United States	0
Tricastin 4	France	71.7	Hope Creek	United States	75.2
Nogent 2	France	69.4	Indian Pt 2	United States	56.4
Paluel 2	France	64.4	Indian Pt 3	United States	51.2
Loviisa 1	Finland	84.3	Kewaunee	United States	77.7
Loviisa 2	Finland	87.4	La Salle 1	United States	52.2
TVO 1	Finland	87.8	La Salle 2	United States	53.7
TVO 2	Finland	87.2	Limerick 1	United States	72.8
Bradwell 1	United Kingdom	57.2	Limerick 2	United States	81.7
Bradwell 2	United Kingdom	61	McGuire 1	United States	64.8
Dungeness A1	United Kingdom	59.4	McGuire 2	United States	71.5
Dungeness A2	United Kingdom	60.9	Millstone 2	United States	53.5
Dungeness B1	United Kingdom	32.2	Millstone 3	United States	58.4
Dungeness B2	United Kingdom	34.4	Monticello	United States	72.3
Hartlepool 1	United Kingdom	49.8	Nine Mile Pt 1	United States	59.1
Hartlepool 2	United Kingdom	55.6	Nine Mile Pt 2	United States	64
Heysham A1	United Kingdom	52.8	North Anna 1	United States	70.8
Heysham A2	United Kingdom	56.6	North Anna 2	United States	76.9
Heysham B1	United Kingdom	69.6	Oconee 1	United States	69.3
Heysham B2	United Kingdom	69.7	Oconee 2	United States	69.7
Hinkley Pt A1	United Kingdom	72	Oconee 3	United States	71
Hinkley Pt A2	United Kingdom	72	Oyster Creek	United States	58.9
Hinkley Pt B1	United Kingdom	66.3	Palisades 1	United States	49.6
Hinkley Pt B2	United Kingdom	62.8	Palo Verde 1	United States	67.8
Hunterston B1	United Kingdom	63.8	Palo Verde 2	United States	72.7
Hunterston B2	United Kingdom	63.9	Palo Verde 3	United States	79
Oldbury 1	United Kingdom	58.1	Peach Bottom 2	United States	57.7
Oldbury 2	United Kingdom	60.5	Peach Bottom 3	United States	58.7
Sizewell A1	United Kingdom	58.3	Perry 1	United States	64.4
Sizewell A2	United Kingdom	52.5	Pilgrim	United States	55.6
Sizewell B	United Kingdom	78.7	Point Beach 1	United States	73.5
Stade 1	United Kingdom	81.2	Point Beach 2	United States	76.8
Torness 1	United Kingdom	68.8	Prairie Isl 1	United States	79.6
Torness 2	United Kingdom	70.8	Prairie Isl 2	United States	81.6
Wylfa 1	United Kingdom	59.7	Quad Cities 1	United States	62.7

Average load factors 1992–1999					
Name	**Country**	**Lifetime**	**Name**	**Country**	**Lifetime**
Wylfa 2	United Kingdom	57.7	Quad Cities 2	United States	60.2
Paks 1	Hungary	84.1	River Bend	United States	69.1
Paks 2	Hungary	85.2	Robinson 2	United States	65.2
Paks 3	Hungary	86.1	Salem 1	United States	51.2
Paks 4	Hungary	86.6	Salem 2	United States	49.8
Kakrapur 1	India	46	San Onofre 2	United States	69.5
Kakrapur 2	India	64.2	San Onofre 3	United States	73.1
Madras 1	India	46.1	Seabrook 1	United States	70.9
Madras 2	India	46.1	Sequoyah 1	United States	55.8
Narora 1	India	41.5	Sequoyah 2	United States	59.5
Narora 2	India	47.3	Shearon Harris	United States	76.5
Rajasthan 1	India	20.3	South Texas 1	United States	68
Rajasthan 2	India	46	South Texas 2	United States	70.6
Tarapur 1	India	49	St Lucie 1	United States	74.6
Tarapur 2	India	48.9	St Lucie 2	United States	81.8
Fugen	Japan	62.7	Summer 1	United States	75
Fukushima I 1	Japan	55.6	Surry 1	United States	62.3
Fukushima I 2	Japan	57.8	Surry 2	United States	63.3
Fukushima I 3	Japan	63.2	Susquehanna 1	United States	76
Fukushima I 4	Japan	73.1	Susquehanna 2	United States	80.2
Fukushima I 5	Japan	72.4	Three Mile Isl 1	United States	60.2
Fukushima I 6	Japan	71.9	Turkey Pt 3	United States	64.7
Fukushima II 1	Japan	74.8	Turkey Pt 4	United States	64.8
Fukushima II 2	Japan	70.2	Vermont Yankee	United States	76.1
Fukushima II 3	Japan	70.2	Vogtle 1	United States	82
Fukushima II 4	Japan	80.3	Vogtle 2	United States	85.5
Genkai 1	Japan	69.6	Waterford 3	United States	77.3
Genkai 2	Japan	81.2	Watts Bar	United States	74.5
Genkai 3	Japan	77.2	WNP 2	United States	58.4
Genkai 4	Japan	75.8	Wolf Creek	United States	78.2

APPENDIX 2: DESCRIPTION OF VARIABLES AND VALUES USED FOR THE BASE CASE

The following table defines all of the variables used in the base case economic analysis of the ENHS. In cases for which a rough estimate had to be made, we include a note describing the basis for the estimate.

Note that a number of variables are listed with the note "Not currently used." These variables are not used in any calculations but have been defined in the spreadsheet model because they may be used in future analyses.

TABLE A2: List of variables used in the economic model

Input parameters				
Values used in computation *Variable Name*	*Variable value*	*Units*	*Description of variable*	*Discussion*
Global and unit configuration				
Case Name	Base			
Annual Number Units	50	gen. units/ year	Number of generating units produced per year.	
Interest Rate	0.08	ratio	Annual interest rate.	
Analyzed Year 1	1	year	First year analyzed. (Not currently used.)	
Analyzed Year 2	5	year	Second year analyzed. (Not currently used.)	
Analyzed Year 3	10	year	Third year analyzed. (Not currently used.)	
Analyzed Year 4	20	year	Fourth year analyzed. (Not currently used.)	
Modules Per Unit	1	heat modules/ gen. unit	Number of heat modules used per generating unit.	
Module Power Output	125	MWt	Thermal power output from a single module.	
Turbine Efficiency	0.4	fraction	Conversion efficiency of the turbine.	
Capacity Factor	0.9	fraction	Fraction of power actually produced.	
SG Per Heat Module	8	SG/heat module	Number of steam generators required per heat module.	
Factory Labor Cost	40	$/man-hour	Cost of labor in fabrication factories, including all variable costs of labor. Does not include capital costs of the factory itself or general and administrative costs (accounted for in Factory GA cost fraction).	
Factory GA	0.15	fraction	Allowance for general and administrative costs in the factory. This is applied to the factory labor costs.	
Site Labor Cost	60	$/man-hour	Cost of labor on site, including all variable costs of labor. Does not include capital costs of site facilities.	

Site costs				
Number Units Per Site	1	gen. units	Number of generating units at the plant site.	
Site Management Annual Labor	15,000	man-hours/ year	Number of man-hours for management and operation of the site as a whole. These hours will be divided among the units at a site. This variable does not include the man-hours spent directly for operation and maintenance of the generating units.	
Project development times				
Construction Time	2	years	Time required from start of project to completion of unit. At completion, it is ready for testing.	
Test Time	0.5	years	Time required to test the completed unit for operational readiness.	
Fabrication factories				
SG Base Factory Cost	2,000,00000	$	Cost of a facility to produce base capacity SG units per year.	
SG Base Production Rate	400	SG/year	Base capacity used for determining the capital cost of the steam generator factory.	
SG Factory Scale Factor	0.7	fraction	Parameter indicating the change in capital cost for capacities that are different from the base cost.	
SG Factory Life	30	years	Life of a factory for steam generators.	
Heat Exchanger Base Factory Cost	500,000,000	$	Cost of a facility to produce base-capacity heat-exchanger units per year.	
Heat Exchanger Base Production Rate	50	heat exchangers/ year	Base capacity used for determining the capital cost of the heat exchanger factory.	
Heat Exchanger Factory Scale Factor	0.9	fraction	Parameter indicating change in capital cost for capacities that are different from the base cost. (Not currently used.)	
Heat Exchanger Factory Life	30	years	Life of a factory for heat exchangers.	
Core Base Factory Cost	0	$	Cost of a facility to produce 1000 cores per year, excluding cost of fuel. Note: currently set to 0 since it is accounted for in the heat exchanger fabrication facility.	
Core Base Production Rate	50	cores/year	Base capacity used for determining the capital cost of the core factory.	
Core Factory Scale Factor	0.9	fraction	Parameter indicating the change in capital cost for capacities that are different from the base cost.	
Core Factory Life	30	years	Life of a factory for cores.	
Fabrication and purchase costs and component lifetimes				
Stainless Steel Price	6	$/kg	Price of stainless steel and other specialty metals. These would be appropriate quality for nuclear applications.	The ORNL (1993) suggests $6,000/ton of miscellaneous nonstructural steel be used for nuclear components.
SG Base Fabrication Material Weight	66,000	kg/SG	Cost of materials for fabricating a steam generator for the first ones built.	Weights: Heat transfer tubes 5 ton, inner tubes 1.7 ton, tube sheets 1.2 ton, shell 3.2 ton. Total is 11.1 tons. These figures account for ≈10% waste.

SG Base Fabrication Labor Hours	600	man-hours/ SG	Number of man-hours required for fabricating a steam generator for the first ones built.	There are 613 tubes. Each tube requires ≈5 welds; each weld might take a couple of minutes. Inspection and testing might double the number of hours required.
SG Material Learning Factor	0.9	fraction	Learning factor for materials used per item. Each time the number of units produced doubles, the cost per unit is multiplied by this value. (Not currently used.)	
SG Labor Learning Factor	0.9	fraction	Learning factor for the man-hours required per item. Each time the number of units produced doubles, the cost per unit is multiplied by this value. (Not currently used.)	
SG Life	25	years	Life of a steam generator.	
Heat Exchanger Base Fabrication Material Weight	230,000	kg/heat exchanger	Weight of materials for fabricating a module for the first ones built.	Total weight ≈ 230 ton allowing for some waste. Weights: Elements 50 ton, inner cylinder 62.3 ton, outer cylinder 32 ton, basis 15.4 ton, cover 32.9 ton, balance 32.5 ton.
Heat Exchanger Base Fabrication Labor Hours	2000	man-hours/ heat exchanger	Number of man-hours required for fabricating a module for the first ones built.	
Heat Exchanger Material Learning Factor	na	fraction	Learning factor for materials used per item. (Not currently used.)	
Heat Exchanger Labor Learning Factor	na	fraction	Learning factor for the man-hours required per item. (Not currently used.)	
Core Base Fabrication Material Weight	11,000	kg/core	Weight of material for a core (excluding the fuel), for the first ones built.	Reflector tungsten 9 ton; mechanisms and framework 2 tons stainless steel.
Core Base Fabrication Labor Hours	600	man-hours/ core	Number of man-hours required per core for the first ones built.	There are 16,700 fuel elements per core. Might require two minutes per fuel element plus time required to fabricate and install supporting framework and control mechanisms.
Core Material Learning Factor	0.9	fraction	Learning factor for materials used per item. Each time the number of units produced doubles, the cost per unit is multiplied by this value. (Not currently used.)	
Core Labor Learning Factor	0.9	fraction	Learning factor for the man-hours required per item. Each time the number of units produced doubles, the cost per unit is multiplied by this value. (Not currently used.)	
Core Fuel Required	17,600	kg/core	Amount of fabricated fuel required for a core.	For a uranium core we assume 12.5% enrichment. For a Pu core at 60W/cm^3 Pu 2.0 ton, U dep 15.5 ton, Zr 1.75 ton.
Fuel Enrichment	0.125	fraction	Required enrichment of the fuel.	
U_3O_8 Cost	30	$/kg	Cost of the U_3O_8 feedstock for the fuel.	EIA projections for the years 2010 to 2015 (DOE 2001, Projections).
SWU Cost	85	$/SWU	Cost of the Separative Work Units for enrichment.	EIA enrichment market data (DOE 2001, Enrichment Market).
Module Life	20	years	Life of a heat module.	
Turbine Cost	20,000,000	$/gen. unit	Cost of turbines and all appurtenant equipment (feedwater, etc.) for one generating unit. Assume cost is about $400/kw.	
Turbine Life	30	years	Life of the turbine.	

Pool Life	60	years	Life of the pool. This is the upper limit on the life of the generating unit.	
Transportation costs				
Sea Transportation Distance	5000	km	Distance that the fabricated components must be transported over sea.	
Land Transportation Distance	500	km	Distance that the fabricated components must be transported over land.	
Module Sea Transportation Cost	2	\$/km	Cost per km for sea transport of modules.	
Module Land Transportation Cost	20	\$/km	Cost per km for land transport of modules.	
SG Sea Transportation Cost	0.4	\$/km	Cost per km for sea transport of steam generators.	
SG Land Transportation Cost	4	\$/km	Cost per km for land transport of steam generators.	
Turbine Sea Transportation Cost	3	\$/km	Cost per km for sea transport of turbines and all appurtenant equipment.	
Turbine Land Transportation Cost	30	\$/km	Cost per km for land transport of turbines and all appurtenant equipment.	
Installation costs				
Module Installation Labor	400	man-hours/ module	Number of man-hours required to install one module.	
SG Installation Labor	50	man-hours/ SG	Number of man-hours required to install one steam generator.	
Pool Installation Labor Hours	7000	man-hours/ module	Number of man-hours required for installing a pool. The amount of pool volume is assumed to be proportional to the number of modules. This includes the cost of excavating, installing insulation, decay heat extraction, module supporting structures, and seismic.	
Pool Installation Material Cost	500,000	\$/module	Cost of materials for a pool. This includes materials for lining, decay heat extraction, supporting bridge, seismic isolation, etc.	Cover is 12.5 m^3 SS, balance of SS is 5.5 m^3 for total ≈150 ton SS. Concrete 238 m^3. Excavation is 524 m^3.
Pool Installation Equipment Cost	100,000	\$/module	Cost of on-site equipment needed for the installation. Includes excavators, cranes, concrete mixers, etc.	
Pb–Bi Required Total	2137	tons/ module	Cost of the Pb–Bi for filling the pool. Assume that the pool volume is proportional to the number of modules in a generation unit.	Primary Pb–Bi 95.2 m^3 971 ton, secondary 114.3 m^3 1166 ton.
Pb–Bi Purchase Cost	5000	\$/ton	Price of Pb–Bi.	Cost might be \$4–6/kg for Pb–Bi.
Pb–Bi Installation Labor	100	man-hours/ module	Number of man-hours required to install the Pb–Bi mixture. Assume this is proportional to volume, and volume is proportional to number of modules.	
Turbine Installation Labor	1000	man-hours	Number of man-hours required to install the turbine and all appurtenant equipment.	
Operation and maintenance costs				
NSSS O&M Staff Required	25,000	man-hours/ year	Number of man-hours required for operation and maintenance of the nuclear steam supply system.	Assume that 2–3 operators/ technicians are on site every shift.
NSSS Consumables Costs	10,000	\$/year	Cost of consumables for operating and maintaining nuclear steam supply system for a year.	

Turbine O&M Staff Required	25,000	man-hours/ year	Number of man-hours required for operation and maintenance of the turbine.	Based on EPRI (1989) TAG Exhibit 18, annual O&M cost for fixed and variable O&M (excluding consumables) is roughly $1.6 M/yr. At $60/hr for on-site labor, 25,000 hours per year gives approximately the right value.
Turbine Consumables Costs	20,000	$/year	Cost of consumables for operating and maintaining a turbine for a year.	
Removal costs				
Module Removal Labor	400	man-hours/ module	Number of man-hours required to remove an ENHS module and prepare it for return shipping.	Five men for two weeks.
SG Removal Labor	200	man-hours/ SG	Number of man-hours required to remove a steam generator and prepare it for return shipping.	Five men for one week.
Pool Removal Cost	500,000	$/module	Cost of removing the pool. Assume that the pool volume and cost is proportional to the number of modules.	
Turbine Removal Cost	200,000	$	Cost of removing the turbine and all appurtenant equipment for a generating unit.	
Dismantlement costs and salvage values				
SG Salvage Value	500	$	Salvage value of the steam generator once it has been returned to the factory. This is the net value accounting for the dismantlement costs, value of materials recovered, and any disposal costs. This can be positive (net positive value) or negative (net cost).	
Heat Exchanger Salvage Value	500	$	Salvage value of the heat exchanger once it has been returned to the factory. This is the net value accounting for the dismantlement costs, value of materials recovered, and any disposal costs. This can be positive (net positive value) or negative (net cost).	
Core Salvage Value	-20,000	$	Salvage value of the core once it has been returned to the factory. This is the net value accounting for the dismantlement costs, value of materials recovered, and any disposal costs. This can be positive (net positive value) or negative (net cost).	
Turbine Salvage Value	50,000	$	Salvage value of the turbine once it has been returned to the factory. This is the net value accounting for the dismantlement costs, value of materials recovered, and any disposal costs. This can be positive (net positive value) or negative (net cost).	

APPENDIX 3: COST BREAKDOWNS FOR THE CASES

Tables A3 and A4, below, provide a breakdown of the cost elements for each of the cases analyzed and organizes the cost elements by component. Table A3 lists the annualized costs, and Table A4 lists the first year costs.

Table A3: Breakdown of annualized costs for the cases analyzed

Sum of annualized cost Component	Cost item	Base	Site labor 2×	Factory labor 2×	High SWU price	High U_3O_8 price	High interest rate	Lower capacity factor	Longer construction period
Module/assembled	Delivery	2,597	2,597	2,597	2,597	2,597	2,995	2,597	2,597
	Installation	2,444	4,889	2,444	2,444	2,444	2,819	2,444	2,444
	Removal	524	1,049	524	524	524	419	524	524
	Return	557	557	557	557	557	445	557	557
Module/assembled Total		*6,123*	*9,092*	*6,123*	*6,123*	*6,123*	*6,679*	*6,123*	*6,123*
Module/core	Factory labor	2,811	2,811	5,622	2,811	2,811	3,242	2,811	2,811
	Material	6,722	6,722	6,722	6,722	6,722	7,752	6,722	6,722
	Nuclear fuel	5,537,434	5,537,434	5,537,434	6,147,989	6,630,919	6,385,968	5,537,434	5,537,434
	Salvage/disposal	437	437	437	437	437	349	437	437
Module/core Total		*5,547,405*	*5,547,405*	*5,550,216*	*6,157,960*	*6,640,890*	*6,397,311*	*5,547,405*	*5,547,405*
Module/heat exchanger	Factory labor	9,370	9,370	18,741	9,370	9,370	10,806	9,370	9,370
	Factory overhead	90,473	90,473	90,473	90,473	90,473	124,600	90,473	90,473
	Material	140,556	140,556	140,556	140,556	140,556	162,094	140,556	140,556
	Salvage/disposal	-11	-11	-11	-11	-11	-9	-11	-11
Module/heat exchanger Total		*240,388*	*240,388*	*249,759*	*240,388*	*240,388*	*297,492*	*240,388*	*240,388*
Pool	Equipment rental	8,080	8,080	8,080	8,080	8,080	10,033	8,080	8,080
	Material	40,399	40,399	40,399	40,399	40,399	50,165	40,399	40,399
	Pb–Bi install	485	970	485	485	485	602	485	485
	Pb–Bi purchase	863,326	863,326	863,326	863,326	863,326	1,072,021	863,326	863,326
	Removal	399	399	399	399	399	165	399	399
	Site labor	33,935	67,870	33,935	33,935	33,935	42,138	33,935	33,935
Pool Total		*946,624*	*981,044*	*946,624*	*946,624*	*946,624*	*1,175,124*	*946,624*	*946,624*
Site management	Management	900,000	720,000	360,000	360,000	360,000	360,000	360,000	360,000
Site management Total		*900,000*	*720,000*	*360,000*	*360,000*	*360,000*	*360,000*	*360,000*	*360,000*
Steam generators	Return	1,040	1,040	1,040	1,040	1,040	773	1,040	1,040
	Delivery	7,120	7,120	7,120	7,120	7,120	8,373	7,120	7,120
	Factory labor	20,684	20,684	41,369	20,684	20,684	24,325	20,684	20,684
	Factory overhead	33,285	33,285	33,285	33,285	33,285	46,746	33,285	33,285
	Installation	2,248	4,497	2,248	2,248	2,248	2,644	2,248	2,248
	Material	296,774	296,774	296,774	296,774	296,774	349,012	296,774	296,774
	Removal	1,313	2,626	1,313	1,313	1,313	976	1,313	1,313
	Salvage/disposal	-55	-55	-55	-55	-55	-41	-55	-55
Steam generators Total		*362,410*	*365,971*	*383,094*	*362,410*	*362,410*	*432,809*	*362,410*	*362,410*
Turbines	Return	313	313	313	313	313	216	313	313
	Consumables	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000
	Delivery	3,153	3,153	3,153	3,153	3,153	3,766	3,153	3,153
	Installation	5,330	10,659	5,330	5,330	5,330	6,365	5,330	5,330
	O&M	1,500,000	3,000,000	1,500,000	1,500,000	1,500,000	1,500,000	1,500,000	1,500,000
	Purchase	1,776,549	1,776,549	1,776,549	1,776,549	1,776,549	2,121,585	1,776,549	1,776,549

Sum of annualized cost Component	Cost item	Base	Site labor 2x	Factory labor 2x	High SWU price	High U_3O_8 price	High interest rate	Lower capacity factor	Longer construction period
	Removal	1,765	1,765	1,765	1,765	1,765	1,216	1,765	1,765
	Salvage/disposal	-441	-441	-441	-441	-441	-304	-441	-441
Turbines Total		*3,306,669*	*4,811,999*	*3,306,669*	*3,306,669*	*3,306,669*	*3,652,843*	*3,306,669*	*3,306,669*
NSSS O&M	Consumables	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
	O&M	1,500,000	600,000	300,000	300,000	300,000	300,000	300,000	300,000
NSSS O&M Total		*1,510,000*	*610,000*	*310,000*	*310,000*	*310,000*	*310,000*	*310,000*	*310,000*
Interest during construction	Interest during construction	610,004	613,524	612,248	649,526	680,787	953,952	610,004	3,073,854
Interest during construction Total		*610,004*	*613,524*	*612,248*	*649,526*	*680,787*	*953,952*	*610,004*	*3,073,854*
Grand Total		13,429,622	13,899,423	11,724,732	12,339,700	12,853,891	13,586,210	11,689,622	14,153,473

Table A4: Breakdown of first-year costs for the cases analyzed

Sum of Initial cost Component	Cost item	Base	Site labor 2x	Factory labor 2x	High SWU price	High U_3O_8 price	High interest rate	Lower capacity factor	Longer construction period
Module/assembled	Delivery	25,500	25,500	25,500	25,500	25,500	25,500	25,500	25,500
	Installation	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000
	Removal	0	0	0	0	0	0	0	0
	Return	0	0	0	0	0	0	0	0
Module/assembled Total		49,500	49,500	49,500	49,500	49,500	49,500	49,500	49,500
Module/core	Factory labor	27,600	24,000	55,200	27,600	27,600	27,600	24,000	24,000
	Material	66,000	66,000	66,000	66,000	66,000	66,000	66,000	66,000
	Nuclear fuel	54,367,345	54,367,345	54,367,345	60,361,865	65,103,345	54,367,345	54,367,345	54,367,345
	Salvage/disposal	0	0	0	0	0	0	0	0
Module/core Total		54,460,945	54,457,345	54,488,545	60,455,465	65,196,945	54,460,945	54,457,345	54,457,345
Module/heat exchanger	Factory labor	92,000	80,000	184,000	92,000	92,000	92,000	80,000	80,000
	Factory overhead	888,274	888,274	888,274	888,274	888,274	1,060,792	888,274	888,274
	Material	1,380,000	1,380,000	1,380,000	1,380,000	1,380,000	1,380,000	1,380,000	1,380,000
	Salvage/disposal	0	0	0	0	0	0	0	0
Module/heat exchanger Total		2,360,274	2,348,274	2,452,274	2,360,274	2,360,274	2,532,792	2,348,274	2,348,274
Pool	Equipment rental	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000
	Material	500,000	500,000	500,000	500,000	500,000	500,000	500,000	500,000
	Pb–Bi install	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000
	Pb–Bi purchase	10,685,000	10,685,000	10,685,000	10,685,000	10,685,000	10,685,000	10,685,000	10,685,000
	Removal	0	0	0	0	0	0	0	0
	Site labor	420,000	420,000	420,000	420,000	420,000	420,000	420,000	420,000
Pool Total		11,711,000	11,711,000	11,711,000	11,711,000	11,711,000	11,711,000	11,711,000	11,711,000
Site management	Management	0	0	0	0	0	0	0	0
Site management Total		0	0	0	0	0	0	0	0
Steam generators	Return	0	0	0	0	0	0	0	0
	Delivery	76,000	76,000	76,000	76,000	76,000	76,000	76,000	76,000
	Factory labor	220,800	192,000	441,600	220,800	220,800	220,800	192,000	192,000
	Factory overhead	355,310	355,310	355,310	355,310	355,310	424,317	355,310	355,310
	Installation	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000
	Material	3,168,000	3,168,000	3,168,000	3,168,000	3,168,000	3,168,000	3,168,000	3,168,000
	Removal	0	0	0	0	0	0	0	0
	Salvage/disposal	0	0	0	0	0	0	0	0
Steam generators Total		3,844,110	3,815,310	4,064,910	3,844,110	3,844,110	3,913,117	3,815,310	3,815,310

Sum of Initial cost Component	Cost item	Base	Site labor 2×	Factory labor 2×	High SWU price	High U_3O_8 price	High interest rate	Lower capacity factor	Longer construction period
Turbines	Return	0	0	0	0	0	0	0	0
	Consumables	0	0	0	0	0	0	0	0
	Delivery	35,500	35,500	35,500	35,500	35,500	35,500	35,500	35,500
	Installation	60,000	60,000	60,000	60,000	60,000	60,000	60,000	60,000
	O&M	0	0	0	0	0	0	0	0
	Purchase	20,000,000	20,000,000	20,000,000	20,000,000	20,000,000	20,000,000	20,000,000	20,000,000
	Removal	0	0	0	0	0	0	0	0
	Salvage/ disposal	0	0	0	0	0	0	0	0
Turbines Total		20,095,500	20,095,500	20,095,500	20,095,500	20,095,500	20,095,500	20,095,500	20,095,500
NSSS O&M	Consumables	0	0	0	0	0	0	0	0
	O&M	0	0	0	0	0	0	0	0
NSSS O&M Total		20,095,500	20,095,500	20,095,500	20,095,500	20,095,500	20,095,500	20,095,500	20,095,500
Interest during construction	Interest during construction	7,549,740	7,546,117	7,577,517	8,038,893	8,425,798	9,508,193	7,546,117	7,546,117
Interest during construction Total		7,549,740	7,546,117	7,577,517	8,038,893	8,425,798	9,508,193	7,546,117	7,546,117
Grand Total		100,071,069	100,023,046	100,439,246	106,554,742	111,683,127	102,271,047	100,023,046	100,023,046

ABBREVIATIONS AND ACRONYMS

AW&ST	Aviation Week & Space Technology
Bi	Bismuth
Btu	British thermal unit
BWR	Boiling water reactor
CCGT	Combined-Cycle Gas Turbine
CNEA	Argentinean National Atomic Energy Commission
CPC	Curtis Power Company
CRIEPI	Central Research Institute of Electric Power Industry (Japan)
DCAC/MRM	Define and Control Airplane Configuration/Manufacturing Resource Management
DER	Designated Engineering Representative
DMIR	Designated Manufacturing Inspection Representative
DOC	U.S. Department of Commerce
DOE	U.S. Department of Energy
EEU	Central and Eastern Europe
EIA	Energy Information Administration
ENHS	Encapsulated Nuclear Heat Source
EPRI	Electric Power Research Institute
FAA	Federal Aviation Administration
4S	Japanese designed SMR
GA	General Atomics
GE	General Electric
GECAS	General Electric Capital Aviation Services
GEES	General Electric Engine Services
HTGR	High-temperature, gas-cooled reactor
IHX	Intermediate Heat Exchanger
IRIS-50	International Reactor Innovative and Secure
JAA	Joint Aviation Authority (European)
JAERI	Japan Atomic Energy Research Institute
KLT-40	Russian designed SMR
kW	Kilowatt
kWe	Kilowatt-electric
kWh	Kilowatt-hour
LAM	Latin America and the Caribbean
LMR	Liquid-metal-cooled reactor
LSPB	Large Scale Prototype Breeder
LWR	Light water reactor
MRX	Japanese designed SMR
MSBWR	Modular Simplified Boiling Water Reactor
MW	Megawatt
MWe	Megawatt-electric
MWh	Megawatt-hour
MWt	Megawatt-thermal
NAM	North America
NRC	Nuclear Regulatory Commission
NERI	Nuclear Energy Research Initiative program
NSSS	Nuclear Steam Supply System
O&M	Operations and maintenance
OKBM	Russian design bureau for mechanical engineering
ORNL	Oak Ridge National Laboratory
PAO	Pacific Organization of Economic Co-operation and Development
PAS	Pacific Asia
Pb	Lead
Pb–Bi	Lead–bismuth
PWR	Pressurized water reactor
RS-MHR	Remote-site modular helium reactor
SG	Steam generator
SMR	Small Modular Reactor
SS	Structural steel
SWU	Separative work units
TAG	Technology Assessment Guide (EPRI)
TC	Type Certification
TPS	TRIGA Power System, U.S.-designed SMR
UCB	University of California at Berkeley
UCRL	University of California Radiation Laboratory, predecessor of Lawrence Livermore National Laboratory
WEU	Western Europe

GLOSSARY

Analysis of variance (ANOVA) A method used to test hypotheses about differences between two or more means. ANOVA does this by examining the ratio of variability between two conditions and the variability within each condition.

Base case

CAREM A Small Modular Reactor (SMR) design being developed by the Argentinean National Atomic Energy Commission (CNEA) and an Argentinian-based commercial supplier, INVAP. It is based on a simplified, integral (its entire primary coolant system is contained within the reactor pressure vessel).

Common variance A term used when comparing the statistics of groups of data. If all of the groups are sampled from underlying statistical processes that all have the same variance, then the groups have a common variance. The value of the common variance is the value of the variance of the underlying statistical processes.

Encapsulated Nuclear Heat Source (ENHS) Developed by a UCB-led consortium, this SMR design includes an LMR that uses either lead or a lead-bismuth alloy as the reactor coolant.

Define and Control Airplane Configuration/Manufacturing Resource Management (DCAC/MRM) A system developed by Boeing to streamline the ordering, configuring, and producing its aircraft.

Factory (manufacturing facility) first-of-a-kind (FOAK) cost FOAK costs include the development of manufacturing specifications, factory equipment, facilities, startup, tooling, and setup of factories that are used for module production.

First commercial plant costs The first plant of its type that is sold to an entity for the purpose of commercial production of electricity. The costs include all engineering, equipment, construction, testing, tooling, project management, and any other costs that are repetitive in nature. Any costs unique to the first commercial plant, which will not be incurred for subsequent plants of the identical design, will be identified and calculated separately. The learning factors for this first plant will reflect its first commercial plant status and not be the average over a larger number of plants.

FOAK plant costs The costs necessary to put a first commercial plant in place that are not be reproduced for subsequent plants. Such costs include research and development, standard plant design, NRC certification of a standard design and prototype, and other such FOAK costs.

4S An LMR that uses sodium as the coolant and is based on principles of simplified operation and maintenance, improved safety and economics, and proliferation resistance. It is being designed by CRIEPI of Japan.

F-test The ratio of two s squares (i.e. estimates of a population variance, based on the information in two or more random samples). When employed in the procedure entitled ANOVA, the obtained value of F provides a test for the statistical significance of the observed differences.

International Reactor Innovative and Secure (IRIS-50) An SMR concept developed by an international consortium led by Westinghouse Electric Company. This PWR is designed to resist proliferation, enhance safety, improve economics, and reduce waste.

KLT-40 An SMR design based on the nuclear steam supply system used in Russian icebreakers. It is a proven, commercially available, small PWR system.

Load-following The process whereby a utility must change the amount of electrical power that it is supplying to the network in order to match user demand. This load varies with time.

Large Scale Prototype Breeder (LSPB) A DOE-funded design for standardizing an 1100-MWe nuclear power plant.

Modular Simplified Boiling Water Reactor (MSBWR) An SMR design concept by GE that incorporates advances in existing, proven BWR technology at the 600 MWe power level.

MRX Originally designed for an icebreaker and scientific observation ship, this SMR design by JAERI is an integral PWR (the steam generator and pressurizer are installed inside the pressure vessel, and the other major components of the primary coolant are outside the reactor vessel).

nth-of-a-kind (NOAK) plant cost The cost of nth of a kind or equilibrium commercial plant of identical design to the first commercial plant, including all engineering, equipment, construction, testing, tooling, project management, and any other costs that are repetitive in nature and will be incurred if an identical plant were built. The NOAK plant reflects the experience of prior plants leading to the NOAK plant.

One-way analysis of variance A statistical procedure for testing hypotheses about the equality of means across groups of sample data. This analysis tests the hypothesis that the groups of data are sampled from underlying statistical processes having equal means. This assumes that the groups have a common variance.

Pb–Bi A lead-bismuth alloy used as coolant in the ENHS SMR design.

Prototype facility and test costs Costs specific to any prototype plant required. These include prototype-specific design, development, licensing, construction, and testing of the prototype to support the standard plant design certification.

Remote-site modular helium reactor (RS-MHR) An SMR concept proposed by General Atomics that is a small nuclear power plant (compressed-helium, gas-cooled reactor) for use in remote areas.

Separative work units A unit of measurement of the work needed to separate the U^{235} and U^{238} atoms in natural uranium in order to create a final product that is richer in U^{235} atoms.

Standard deviation The square root of the variance. It is an indication of (1) how dispersed the probability distribution is about the center, and (2) how spread out on the average are the values of the random variable about its expectation.

Tailored Business Streams Boeing's new business approach to developing commercially successful large airplanes.

Transition period plant-specific capital costs The capital costs for transition plants that exclude any FOAK costs and include costs for manufacturing factory equipment, site construction, site-specific engineering, and home-office construction support. The transition in costs from the first to the NOAK commercial plant and the effects of serial manufacturing and construction will be demonstrated.

TRIGA Power System (TPS) A PWR concept being developed by General Atomics. This SMR is based on the TRIGA reactor design coupled with a commercially available organic power system.

U–Zr Uranium and zirconium. A metallic alloy used as fuel in the ENHS SMR design.

Variance A measure of how spread out a distribution is. It is computed as the average squared deviation of each number from its mean.

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